Investigating the Potential for Green Infrastructure to Mitigate the Urban Heat Island Effect in Columbus, Ohio

Julia M. Stowe

April 14, 2020

Department of Civil, Environmental, and Geodetic Engineering

Advisor: Dr. Ryan Winston

Abstract

The urban heat island (UHI) effect is the thermal enrichment of air in urban environments caused by the presence of traditional urban infrastructure and human activities. As urban areas develop, vegetation, which contributes to evapotranspiration and thus cooling effects in the outdoor air, is replaced with low-albedo, or low-reflectivity, surfaces that absorb heat. Green infrastructure, including green roofs and bioretention cells, is typically designed for stormwater treatment but its co-benefits may include mitigation of the UHI effect by increasing plant density and reducing the presence of low-albedo surfaces in urban areas. Bioretention cells and green roofs in four distinct neighborhoods of Columbus, Ohio, were outfitted with sensors to record air temperature every minute at ground level and two feet above the surface. Each treatment site was compared with a nearby control of traditional infrastructure with identical measurement techniques. The bioretention cells, green roofs, and their controls all had varying characteristics including size, design, surrounding land use, and plant species and density. Of the bioretention cells analyzed, three were considered not able to mitigate the UHI effect compared to their controls; one could somewhat, and one could considerably mitigate the UHI effect. Of the five green roofs analyzed, two could somewhat mitigation the UHI effect and one had considerable mitigation capacities at 60 cm. Based on the controls used and temperature difference results, grassy areas and white roofs may also contribute to UHI effect mitigation. Shading of sites throughout the day may also have a notable effect on results. Green infrastructure design is crucial to assess contribution to UHI effect mitigation but is highly dependent on control comparisons in the nearby area and should be assessed on a case-by-case basis. Bioretention cells and green roofs have the capacity to mitigate the UHI effect to a noticeable degree and thus UHI effect mitigation should be considered as a possible co-benefit.

Acknowledgements

I would like to acknowledge first and foremost my research advisor, Dr. Ryan Winston, who has been instrumental in the coordination of this research effort and development of this thesis. His guidance and support have been greatly appreciated. I would also like to thank Kathryn Boening for obtaining funding for this project and coordinating equipment deployment and data collection efforts. I would like to thank the Sustainability Institute at The Ohio State University for providing funding for this project and the various building operators, campus facility staff, and city officials who allowed for sensor installation on their properties with coordinated data collection efforts. I would also like to thank the Department of Food, Agricultural, and Biological Engineering at Ohio State for continued research support regarding green infrastructure. I would like to thank Dr. Gil Bohrer for his review of and comments on this document.

Table of Contents

List of Figures

List of Tables

Introduction

The urban heat island (UHI) effect causes a rise in local air temperatures in urban environments due to the presence of urban infrastructure and human activities (Yang et al. 2016). According to a study on the energy of UHIs by Oke (1982), the temperature difference between urban and nearby surrounding rural areas can exceed 10°C. Unfortunately, these differences are asymmetric with respect to season, with average differences of 4.3°C in the summer and 1.3°C in the winter (Imhoff et al. 2010). This means that heat stress during the hot summer months is further exacerbated in urban areas.

Urban areas have high-density populations that produce more heat per area for climate-control in homes, businesses, and travel compared to surrounding rural areas. As urban areas develop, vegetation, which contributes to evapotranspiration and thus cooling effects to the outdoor air, is replaced with low-albedo, or low-reflectivity, surfaces that absorb heat (Stone et al. 2010). Impervious surface area is the primary driver for the UHI, explaining 70% of the total variance in land surface temperature in one study (Imhoff et al. 2010). The survival of most plant and animal species is climate driven; warmer and drier conditions in urban areas will modify which species are present and their activity levels in a given urban region (Sexton et al. 2009; Ackley et al. 2015; Kaiser et al. 2016).

Urban heat islands create many negative effects such as an increase in energy demand, particularly in the summertime, for cooling purposes which in turn outputs more greenhouse gases; these contribute to smog formation with warmer air temperatures that encourage ozone formation close to Earth's surface (Synnefa et al. 2011). Though beneficial in the upper atmosphere to protect the Earth from the sun's UV rays, ozone near the Earth's surface can cause breathing problems that are especially harmful to people with cardiovascular diseases and asthma (Yang & Omaye 2009). Heat stroke and exhaustion are common maladies related to higher urban temperatures (Ichinose et al. 2008) which preferentially target susceptible populations such as the elderly, manual laborers, and people of lower socio-economic status without access to air conditioning.

The urban heat island effect in Phoenix, Arizona has more than doubled the yearly "misery hours" for humans (i.e., temperature-humidity index >38°C) (Ruddell et al. 2013). According to the Center for Disease Control, 8,081 deaths related to heat stress were reported in the United

States from 1999 to 2010 and the vast majority of them (81%) occurred in urban areas. Almost all heat-related deaths occurred during May – September (CDC). The urban heat island effect must be addressed to minimize these negative human health, ecological, and environmental effects.

Beyond the UHI effect, impervious surfaces also impact stormwater runoff generation, causing large runoff volumes (Jartun et al. 2008), flooding, and water pollution (Xiao et al. 2016). Stormwater generated during rainfall events would ordinarily infiltrate green spaces, however with the influx of impervious surfaces in urban areas the stormwater is unable to infiltrate and subsequently creates runoff. As such, engineers implement stormwater control measures (SCM) to partially mitigate some of these impacts of urbanization (Fletcher et al. 2015). Cities may choose to implement green infrastructure, novel techniques used to reduce runoff volume, or traditional infrastructure like sewer inlets, pipes, and ponds. Green infrastructure (GI) techniques, including bioretention and green roofs, are primarily designed for stormwater control (e.g., Voyde et al. 2010; Moore and Hunt 2012; Fassman-Beck et al. 2016; Winston et al. 2016) but may have co-benefits to habitat, cultural services, and carbon sequestration (Kazemi et al. 2009; Bouchard et al. 2013; Alves Beloqui et al. 2019).

The potential for GI to mitigate the UHI effect is another as yet poorly quantified co-benefit in utilizing green over traditional infrastructure. Particularly for bioretention and green roofs, they may reduce the UHI effect through evapotranspiration from the SCM and since their presence reduces total impervious area. However, little research into this potential co-benefit for bioretention cells has been conducted but might be critical to consider when assessing the total return on investment between green and traditional stormwater control infrastructure.

Various studies regarding the effect of green roofs on UHI effect mitigation have been conducted, including a study in Adelaide, South Australia. Air temperatures measured 60 cm above prototype-scale green roofs were found to be 2-5°C cooler during the day and 3-6°C warmer at night than standard control roofs (Razzaghmanesh et al. 2016). Another study monitoring four areas of New York City determined that an average 2°C air temperature difference exists between the most and least vegetated areas (Susca et al. 2011). This study also assessed the construction, replacement, and use of traditional, white, and green roofs and determined that white and green roofs are less impactful on climate based on carbon dioxide equivalents than traditional black roofs due to “thermal resistance, biological activity of plants, and surface albedo” (Susca et al. 2011).

However, data are lacking regarding bioretention cell contribution to UHI mitigation; we were unable to find any studies that quantified air temperature immediately above this SCM (Endreny 2008). The additional research done regarding bioretention cells and their effect on mitigating the UHI effect may increase their ecosystem valuation and thus considered benefits when cities determine if their installation will be beneficial.

The current research will provide additional quantifiable information to city planners, engineers, and landscape architects on benefits of installing GI to address issues related to UHIs. The goals of the current study were to (1) analyze bioretention and green roof function to give a more comprehensive view of GI function for mitigation of the UHI effect, (2) explore how differing SCM characteristics, such as size and surrounding land use, contribute to having a greater or lesser effect on UHI mitigation, and (3) determine whether air temperature in green infrastructure differed from nearby control locations.

Methodology

Site Selection

Green roofs and bioretention cells in Columbus, Ohio and surrounding suburbs were identified to serve as candidate study locations. Coordination with building operators, campus facility staff, and city officials ultimately led to favored locations for the study. These locations generally provided a relative ease of access for data download and contributed to a variety of SCM design characteristics overall. Further, a representative cross-section of locations (downtown, Ohio State University campus, and residential neighborhoods) within the Columbus region were selected to provide a variety of contexts for the study (Figure 1).

In total, five green roofs and seven bioretention cells were monitored for UHI mitigation. They were located in downtown Columbus, on Ohio State University’s campus, and in the residential neighborhoods of Clintonville and Upper Arlington. For each green roof, a nearby control roof (i.e. standard roof without vegetation) was monitored in exactly the same fashion as the SCM. Similar paired treatment and control sites were monitored for bioretention cells, with standard streets without bioretention serving as experimental controls. The controls for bioretention cells were located between the curb and sidewalk to mimic typical street-side bioretention cell locations. The green roof controls were located on a nearby traditional roof at the same or similar elevation.

In all cases, attempts were made to locate control sites with similar tree cover, average daily traffic (in the case of roads), and nearby buildings (in the case of green roofs) to ensure realistic air temperature comparisons. Bioretention control sites were located less than one mile from the SCM (Figure 1) and the furthest roof control was located on an adjacent building, no more than 350 m from the SCM.

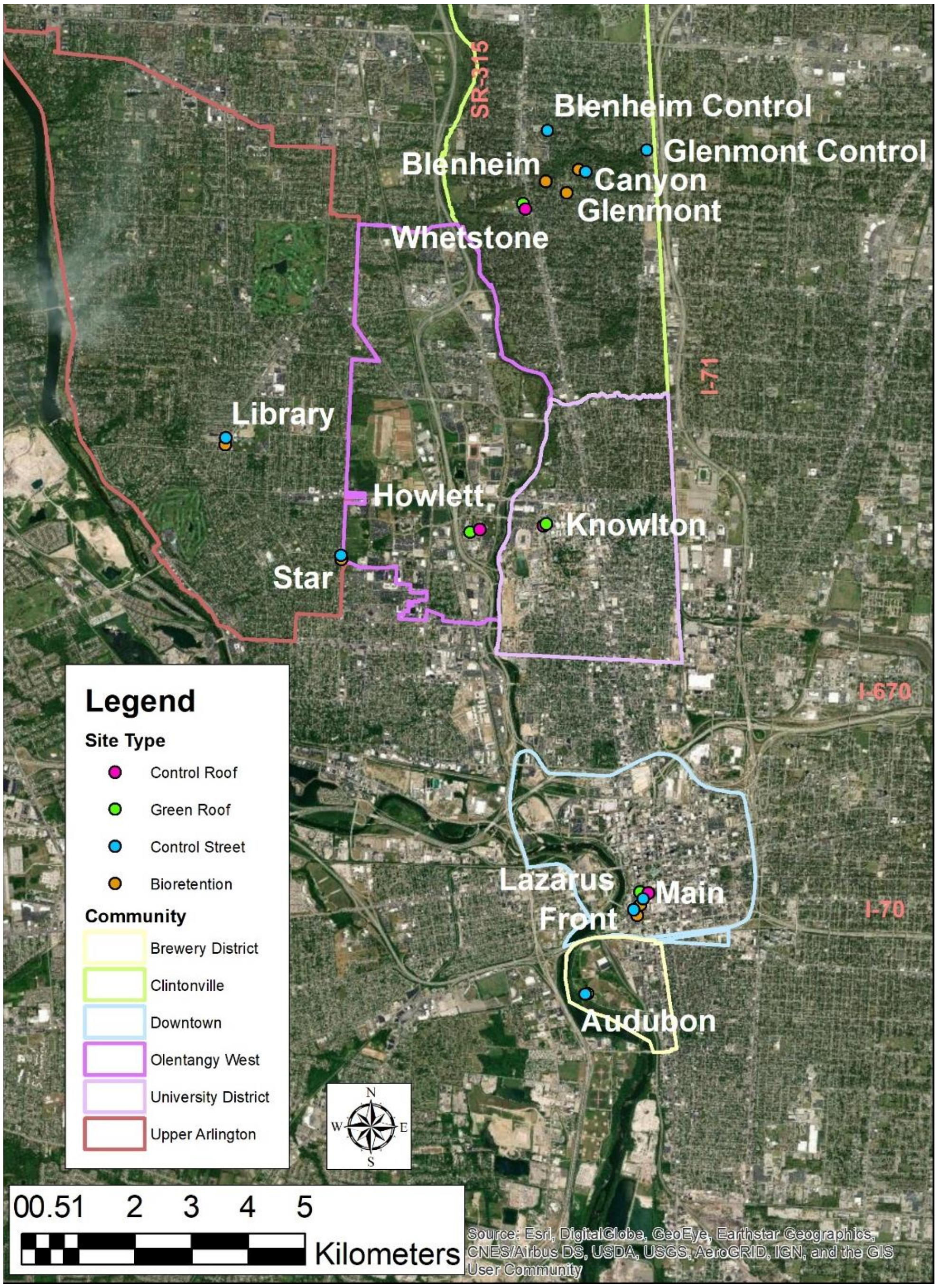


Figure 1. Sensor locations in communities around Columbus, Ohio.

Blueprint Columbus is an ongoing effort by the City of Columbus, Ohio, to install green infrastructure in the Clintonville neighborhood to mitigate sanitary sewer overflows (SSOs). Many Blueprint Columbus bioretention cells were chosen due to The Ohio State University's ongoing research efforts associated with Blueprint and thus familiarity and accessibility to the sites. Established bioretention cells in Upper Arlington and in downtown Columbus were also selected for monitoring (Table 1 and Figure 1). Green roofs were located in Clintonville (1), on OSU campus (2), and in ultra-urban downtown Columbus (2; Table 1 and Figure 2). The locations vary greatly in many ways, such as size of the SCM, surrounding area, elevation, and plant cover (Table 1). These parameters were considered when analyzing which sites had a greater effect on UHI effect mitigation and how specific characteristics may contribute to differing results between sites. Below in Figure 2 and Figure 3 are three samples of bioretention and green roof locations highlighting different designs. Refer to Appendix A for pictures of each of the sites individually.

Figure 2. Three example bioretention cells. From left to right: Blenheim, Canyon, Main. Refer to Figure 1 for locations and Appendix A for pictures of all sites.

Figure 3. Three example green roofs. From left to right: Audubon, Lazarus, Whetstone. Refer to Figure 1 for locations and Appendix A for pictures of all sites.

Table 1. Sensor Placement Locations and their Characteristics

Location	Area of Columbus	SCM Type	Area (m^2)	Relative Plant Height	Surrounding Area	Control Description
Audubon	Downtown	Green Roof	757	Low	Vegetated	White roof intermixed with green roof
Blenheim	Clintonville	Bioretention Cell	35	Medium	Suburban	Above grass
Canyon	Clintonville	Bioretention Cell	127	Medium	Suburban	Above grass
Front	Downtown	Bioretention Cell	6.7	Medium/High	Urban	Above sidewalk
Glenmont	Clintonville	Bioretention Cell	71.9	Medium	Suburban	Above grass
Howlett	Campus	Green Roof	1,027	Low	Suburban	White roof on adjacent building
Knowlton	Campus	Green Roof	350	High	Urban	Traditional roof on same building
Lazarus	Downtown	Green Roof	1,276	Medium	Urban	Traditional roof on same building
Library	Upper Arlington	Bioretention Cell	182	Medium/High	Suburban	Above sidewalk
Main	Downtown	Bioretention Cell	11.1	Medium/High	Urban	Above sidewalk between buildings
Star	Upper Arlington	Bioretention Cell	58	Medium/High	Suburban	Above grass
Whetstone	Clintonville	Green Roof	120	Low	Suburban	White roof on same building

Note: Area indicates area of vegetative cover for the SCM.

Instrumentation

HOBO Pendant® MX2201 temperature sensors were deployed inside solar radiation shields, both sourced from Onset Computer Corporation, at green infrastructure and control locations. The temperature sensors were attached to the inside of the solar radiation shields to prevent sunlight from heating the sensors and thus causing temperature readings to be higher than the actual surrounding atmospheric temperature. Furthermore, the solar radiation shields were vented to allow wind to pass over the sensor and to prevent rain from impacting air temperature measurements. The solar radiation shields, with sensors attached, were deployed at ground level and 60 cm above the ground at each location (Figure 2). This parallels the methodology applied in the aforementioned pilot study in Australia by Razzaghmanesh and others; however portable recording thermometers were used by Razzaghmanesh and others which likely do not measure ambient air temperature without including effects of solar radiation.

Figure 4. Configurations of temperature sensors; from left to right: green and control roof, bioretention cell, street control.

For green roof locations and their controls, a wooden post was cemented into a 19-liter bucket. The ground-level solar radiation shield was then attached to the side of the bucket while the 60-cm shield was attached to the wooden post cemented within the bucket (see left image in Figure 4). For the bioretention cells, the shields were attached to a single wooden post driven into the ground (see middle image in Figure 4). For bioretention cell controls, the shields were attached with zip ties at 0 and 60 cm heights to nearby stationary objects, such as street signs and lamp posts, above traditional street-side landscapes (see right image in Figure 4).

Data Collection

Sensors were programmed to record air temperature every minute; data were stored on internal memory within the sensor. Every two months, the sensor data were downloaded utilizing Bluetooth technology to the HOBOmobile App, which was used to export the collected data to a spreadsheet. Data sets included date/time stamps and temperature readings in Fahrenheit. A master spreadsheet was then compiled with all the temperature readings for each site at each recorded time step. Some sensors were deployed earlier than others and thus various locations had different data collection dates; Appendix C contains information regarding the exact dates and times each sensor collected data. Various sensors had missing temperature data sets due to challenges with data download intervals. This issue was corrected as time went on by creating a schedule to download data from the sensors every month and a half to ensure no data were lost.

Data Analysis

The temperature data were analyzed in R statistical software version 3.6.2 to determine if there was a significant difference in temperature readings. Comparisons were made among different measurement heights at a single site, between treatment and control sites at ground level, and between treatment and control sites at the 60-cm level. RStudio was also utilized to create meaningful tables and figures of the temperature data. Statistical analysis was performed using the resultant p values of a paired t-test; normality was not tested as the data set for each location contained hundreds of thousands of data points. Thus, we assume we are approximating the population of temperature data rather than taking a sample of the population. A criterion of 95% confidence ($\alpha = 0.05$) was utilized in this research unless stated otherwise.

For each site, the amount of time temperature difference ranges occurred was quantified (Table 2). A 0-3°F temperature difference between control and treatment sites was considered a minimal difference, 3-8°F a moderate difference, and greater than 8°F a substantial difference. In this way, measured temperature differences were categorized for comparison and discussion.

Table 2. Temperature Difference Classifications

Temperature Difference (°F)	Classification
0-3	Minimal
3-8	Moderate
>8	Substantial

Temperature data from September 11-13, 2019 was analyzed for each location to determine when it is likely that peak differences between treatment and control occur throughout the day. This time period was chosen because each day reached temperatures in excess of 90°F which is well above average for Columbus, Ohio. Based on the aforementioned parameters, the site design will be analyzed to see if it contributes to the mitigation of the UHI effect.

Results & Discussion

A paired t-test indicated that there were significant differences in air temperature between the treatment and control site at 0 cm for every location aside from Knowlton, a green roof. Knowlton may have not been significantly different at ground level because it was a highly intensive green roof with shrubs and trees; therefore, much of the evapotranspiration and thus cooling effects would be happening higher in the atmosphere which was indicated by the significant difference in temperature readings at 60 cm. There were also significant differences between temperature readings at the control and treatment sites at 60 cm for every location aside from Audubon, a green roof. Audubon may have not had a significant difference at 60 cm because the vegetation on the green roof was very low to the ground. The control roof for Audubon was also white which reflects solar radiation and would not absorb as much heat as a traditional roof which therefore led to a lower temperature difference. However, there were other sites with white roof controls (Howlett, Whetstone) that did have significant differences, but the white roof at Audubon is intermixed with the green roof which may lead to more effective cooling in total between both sites. All the resulting p values from the paired t-tests are displayed in Table 3 below.

Table 3. Paired t-test Resultant P Values

Location	Treatment 0 vs 60 cm	Control 0 vs 60 cm	Control vs Treatment 0 cm	Control vs Treatment 60 cm
Audubon	0.000	0.000	0.000	0.220
Blenheim	0.000	0.000	0.000	0.000
Canyon	0.000	0.676	0.000	0.000
Front	0.763	0.027	0.000	0.003
Glenmont	0.000	0.264	0.000	0.000
Howlett	0.154	0.162	0.000	0.000
Knowlton	0.000	0.547	0.167	0.000
Lazarus	0.000	0.000	0.000	0.000
Library	0.000	0.025	0.000	0.000
Main	0.000	0.000	0.000	0.000
Star	0.200	0.000	0.000	0.000
Whetstone	0.000	0.003	0.000	0.000

Note: Values highlighted indicate that the resultant p value shows a significant difference between the sensors in the corresponding column heading.

Three locations did not have a significant difference between temperature readings for the treatment site at 0 and 60 cm heights and 4 sites did not have a significant difference between temperature readings for the control site at 0 and 60 cm heights (Table 3). This means that there is no clear gradient in air temperature near the ground. It is unclear why this disparity may have occurred as there seems to be no pattern between sites of similar characteristics and their significant differences. It is recommended for future research that a greater height difference between the ground and upper sensor be analyzed to see the effect on air temperature at a height more akin to what humans would experience, such as 1.5 m – 2 m.

Table 4 below details the average differences between the treatment and control sensors at 0 cm for each month of data collection. Though the p values from the paired t-test indicated significant differences at all sites at 0 cm aside from Knowlton, the averages overall are fairly low with the highest average recorded difference being 2.22°F higher at the control site in September 2019 at Glenmont and the lowest being 1.28 °F higher at the treatment site at Lazarus in January. Therefore, the average temperature differences at 0 cm between the treatment and control sites are considered minimal. At five of the treatment sites, higher average temperatures were observed in the winter than at control sites. These are examples of the thermal buffering that SCMs can provide in the winter, where temperature is moderated in the opposite direction of UHI mitigation.

Table 4. Monthly Average Temperature Differences between Treatment and Control at 0 cm

Site	Average Temperature Difference (°F)									
	Jun-19	**Jul-19**	**Aug-19**	**Sep-19**	**Oct-19**	**Nov-19**	**Dec-19**	**Jan-20**	**Feb-20**	**Mar-20**
Audubon	0.22	-0.51	0.06	--	0.87	1.26	1.69	0.78	0.53	0.30
Blenheim	--	--	--	--	--	-0.29	-0.38	-0.28	-0.32	-0.98
Canyon	--	-0.59	0.41	0.64	0.40	0.33	0.38	-0.15	-0.03	0.03
Front	--	--	-0.89	-1.14	-0.69	-0.12	0.27	0.24	0.32	-0.18
Glenmont	--	--	1.09	2.22	2.12	1.58	1.51	0.27	0.72	1.04
Howlett	--	0.83	0.29	1.20	--	--	--	--	--	--
Knowlton	--	0.32	-0.28	0.06	--	--	--	0.96	0.59	0.68
Lazarus	1.14	0.70	0.81	0.90	0.59	--	0.21	-1.28	-1.18	-0.72
Library	--	0.56	0.12	--	--	--	--	0.24	0.64	1.04
Main	--	--	1.17	1.70	0.96	0.43	0.48	0.22	0.28	0.67
Star	0.71	0.53	0.72	1.03	1.29	--	--	0.00	0.62	0.96
Whetstone	--	--	0.15	0.91	1.75	1.49	1.33	0.61	--	--

Note: A positive value indicates the control sensor had a higher temperature reading than the treatment sensor. Please refer to Table 1 for location characteristics including SCM type. Refer to Appendix C for the exact dates and times data was recorded for each sensor.

Table 5 below details the average differences between treatment and control temperatures at 60 cm. Generally, differences in temperature at 60 cm were smaller in magnitude than those observed at ground level, showing decreasing impacts of SCMs with increasing height above the SCM. The maximum average temperature difference at 60 cm was 1.55°F at the Main bioretention cell in September 2019. Four treatment sites saw higher temperatures at 60 cm during the winter than control sites, similar to what was observed at ground level.

Table 5. Monthly Average Temperature Differences between Treatment and Control at 60 cm

Site	Average Temperature Difference (°F)									
	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20	Mar-20
Audubon	-0.10	-0.15	-0.35	0.27	-0.49	0.35	0.46	0.26	0.16	0.13
Blenheim	--	--	--	--	--	-0.58	-0.32	-0.32	-0.33	-0.19
Canyon	--	--	0.31	0.41	0.21	-0.04	0.01	-0.21	-0.18	0.04
Front	--	--	-0.18	-0.42	-0.23	-0.09	-0.04	0.02	0.02	-0.27
Glenmont	--	--	0.53	1.44	1.62	1.24	1.13	0.27	0.39	0.47
Howlett	--	1.22	1.05	1.32	--	--	--	--	--	--
Knowlton	--	1.12	0.31	0.67	--	--	--	0.54	0.23	0.59
Lazarus	0.27	0.00	-0.07	-0.10	-0.66	-1.49	-1.69	-1.72	-1.59	-1.13
Library	--	0.23	0.11	--	--	--	--	0.12	0.15	0.20
Main	--	--	0.96	1.55	0.89	0.41	0.22	0.18	0.28	0.53
Star	0.68	0.36	0.16	0.48	0.41	--	--	0.25	0.52	0.55
Whetstone	--	--	1.22	1.52	1.11	0.82	0.56	0.48	--	--

Note: A positive value indicates the control site had a higher temperature reading than the treatment site. Please refer to Table 1 for location characteristics including SCM type. Refer to Appendix C for the exact dates and times data was recorded for each sensor.

Because many of the sites had an average difference indicating that the control site had a lower temperature reading than the treatment site, it cannot be concluded that the significant difference as determined by the paired t-test corresponds to treatment sites having lower measured temperatures than their paired controls. In some cases, particularly those with many negative averages over the months such as at Lazarus at 60 cm, it is likely that the control site on average had lower measured temperatures than the treatment site. However, it is important to consider that the temperatures were measured continuously throughout the day and the averages account for temperatures at night, when UHI is not a factor, as well as during the day. It is likely that the measured temperatures at night would have lower differences as it is cooler at night, especially in the summer. Therefore, it is most important to consider the minimum and maximum temperature differences as mitigating the UHI effect involves lowering extreme temperatures.

Table 6 and Table 7 display the minimum and maximum temperature measurements for each site at heights of 0 and 60 cm, respectively, during each month the sensors collected data. The minimum and maximum temperature readings show substantial differences between sites with the control measuring up to 17.91°F higher than the treatment site at 0 cm and up to 22°F more at 60 cm. However, the treatment sites also measured up to 15.75°F more than the control site at 0 cm and 31.12°F more than the control site at 60 cm. Therefore, it is important to determine at what time of day these differences occurred to examine if they would provide UHI effect mitigation when high temperatures are most damaging, such as midafternoon when people are outdoors and more likely to suffer negative health effects related to the UHI effect. The following sections will analyze each type of SCM, bioretention cells and green roofs, overall as well as specific locations to determine when minimum and maximum differences likely occurred during the day and how the site characteristics may have contributed to results. The locations will be analyzed over a shorter period, from September 11 to September 13, 2019 as these days had temperatures in excess of 92°F, which were some of the hottest days during the measurement period. Individual data collected at each site with accompanying figures can be found in Appendix B.

Table 6. Monthly Minimum and Maximum Temperatures Differences Between Treatment and Control Sites at 0 cm

Site	Min or Max	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20	Mar-20
Audubon	Min	-7.03	-14.36	-2.86	--	-9.66	-10.65	-6.56	-7.19	-6.57	-6.95
	Max	5.64	7.49	1.63	--	11.73	13.59	17.91	11.82	7.42	6.33
Blenheim	Min	--	--	--	--	--	-12.36	-10.51	-8.49	-12.12	-9.58
	Max	--	--	--	--	--	10.58	13.82	7.88	9.96	3.02
Canyon	Min	--	--	-15.75	-12.20	-10.97	-5.72	-7.03	-5.79	-4.40	-5.41
	Max	--	--	11.89	12.59	12.82	9.50	6.10	3.71	5.72	7.26
Front	Min	--	--	-9.19	-8.49	-7.64	-6.41	-4.63	-4.71	-7.10	-7.34
	Max	--	--	3.71*	3.56	2.55	2.17	3.71	1.94	3.25	2.24
Glenmont	Min	--	--	-9.73	-11.12	-8.34	-9.11	-5.33	-8.27	-8.88	-7.18
	Max	--	--	10.35	15.29	13.36	11.51	9.73	8.18	13.98	8.19
Howlett	Min	--	-12.20	-15.21	-9.50	--	--	--	--	--	--
	Max	--	9.11	8.65	7.26	--	--	--	--	--	--
Knowlton	Min	--	-12.43	-12.75	-11.66	--	--	--	0.15	-5.10	-1.62
	Max	--	13.51	17.30	11.50	--	--	--	2.01	7.11	2.62
Lazarus	Min	-3.09	-6.26	-6.49	-7.33	-7.80	--	-8.72	-10.58	-11.27	-7.80
	Max	4.71	7.18	8.42	8.50	8.26	--	9.96	4.24	4.71	4.17
Library	Min	--	-6.26	-6.03	--	--	--	--	-5.25	-5.56	-5.33
	Max	--	5.80	4.56	--	--	--	--	9.65	13.44	12.36
Main	Min	--	--	-4.33	-2.17	-3.63	-2.08	-3.55	-1.93	-1.77	-1.47
	Max	--	--	7.57	8.88	8.18	5.86	8.57	5.02	4.87	5.63
Star	Min	-6.41	-9.57	-10.12	-9.11	-8.11	--	--	-4.17	-5.49	-4.33
	Max	10.88	7.80	8.19	8.34	7.88	--	--	4.94	9.96	6.95
Whetstone	Min	--	--	-7.02	-3.16	-2.48	-4.48	-4.40	-2.16	--	--
	Max	--	--	5.02	10.34	14.06	12.20	12.97	11.97	--	--

Note: Positive values indicate that the control site had a higher temperature than the treatment site. Dashes indicate data was not recorded due to sensor malfunction or data loss. Please refer to Appendix C for exact dates and times of data collection for each sensor.

*The maximum reading of 18.53 °F for Front in August 2019 was not considered as it was an outlier. The next highest reading for Front is displayed. Please refer to the Results & Discussion section, Front subsection for further discussion.

Table 7. Monthly Minimum and Maximum Temperature Differences Between Treatment and Control Sites at 60 cm

Site	Min or Max	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20	Mar-20
Audubon	Min	-4.87	-5.71	-18.77	-22.70	-31.12	-3.40	-2.08	-2.32	-3.86	-4.24
	Max	1.93	3.25	14.06	22.00	21.78	4.09	5.79	3.93	3.55	3.32
Blenheim	Min	--	--	--	--	--	-11.66	-8.57	-3.70	-3.79	-2.39
	Max	--	--	--	--	--	7.95	7.80	1.85	3.71	2.40
Canyon	Min	--	--	-6.33	-5.02	-5.10	-4.02	-3.94	-3.40	-4.10	-2.24
	Max	--	--	5.41	6.41	7.42	4.86	4.17	2.24	4.10	6.02
Front	Min	--	--	-5.41	-5.64	-4.10	-3.94	-4.71	-3.24	-4.02	-4.64
	Max	--	--	5.64	4.02	2.32	2.40	2.70	4.17	2.00	1.70
Glenmont	Min	--	--	-8.72	-9.27	-6.72	-7.10	-5.25	-3.78	-5.48	-3.17
	Max	--	--	9.42	9.27	8.96	9.35	8.65	5.71	7.80	5.56
Howlett	Min	--	-5.17	-3.01	-1.70	--	--	--	--	--	--
	Max	--	9.50	10.11	10.11	--	--	--	--	--	--
Knowlton	Min	--	-7.49	-7.26	-6.18	--	--	--	-0.08	-3.79	-1.16
	Max	--	13.67	17.45	11.59	--	--	--	1.39	4.63	3.48
Lazarus	Min	-3.55	-5.33	-6.02	-6.95	-8.34	-12.20	-12.12	-11.51	-13.05	-8.96
	Max	2.78	3.40	6.10	3.32	3.78	2.55	2.63	1.55	1.47	1.47
Library	Min	--	-6.87	-4.48	--	--	--	--	-3.01	-3.86	-3.25
	Max	--	5.09	3.78	--	--	--	--	2.94	4.02	3.56
Main	Min	--	--	-3.16	-3.08	-2.63	-2.40	-3.94	-1.39	-2.62	-1.70
	Max	--	--	7.65	8.50	7.88	6.48	7.96	6.33	6.03	8.19
Star	Min	-4.41	-7.64	-8.96	-7.41	-6.95	--	--	-2.00	-3.16	-1.93
	Max	5.10	6.64	5.64	5.87	5.79	--	--	3.63	6.64	5.63
Whetstone	Min	--	--	-3.17	-1.70	-2.01	-1.09	-1.39	-1.01	--	--
	Max	--	--	7.80	7.57	7.26	8.34	8.49	7.64	--	--

Note: Positive values indicate that the control site had a higher temperature than the treatment site. Dashes indicate data was not recorded due to sensor malfunction or data loss. Please refer to Appendix C for exact dates and times of data collection for each sensor.

Bioretention Cells

All the bioretention cell locations had a significant difference between the control and treatment sites at 0 and 60 cm. All the average temperature differences between treatment and control at 0 cm and at 60 cm were positive for Glenmont, Library, Main, and Star, indicating that the significant difference likely corresponded with higher temperature readings at the control site compared to the treatment site. At Blenheim, all the average temperature differences were negative; however, data was only recorded at this site from November 2019 until early March 2020 due to sensor malfunctions. Therefore, Blenheim will not be considered in analyzing bioretention cell effects on mitigating the UHI effect as the months data were collected do not correspond with months that are ordinarily characterized by high temperatures. Further, it is logical that SCMs may be a source of heat during the winter months.

For both the 0 cm and 60 cm heights, Front had a negative average difference between the control and treatment site until November indicating that the significant difference likely corresponds to the treatment site having a higher temperature than the control site. Canyon had a positive average difference at 0 cm from August to December and March and at 60 cm from August to October, December, and March. The positive average difference between treatment and control for the warmest months likely corresponds to a significant difference with the control site having higher temperatures than the treatment site. The positive average differences are likely due to the evapotranspiration by the plants cooling the atmosphere for most of the time data was recorded.

In the following sections, Canyon, Front, Glenmont, Main, and Star will be analyzed to see how many days moderate and substantial temperature differences between the treatment and control sites occurred, when those differences likely occurred during the diurnal variations in temperature that occur daily, and how site characteristics may have contributed to the results. Library is not analyzed because it is lacking data for large time periods, including the period of interest, September 11-13, 2019.

Canyon

At Canyon, there were far more moderate and substantial temperature differences between treatment and control at 0 cm than at 60 cm (Table 8).

Table 8. Duration of Temperature Difference Classifications for Canyon at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	339	91
Substantial (>8 °F)	57.6	0

In analyzing the period from September 11-13, 2019, the trend of differences throughout the day was very similar at 0 cm and 60 cm, but the magnitudes of the differences were notably different as the peak difference at 0 cm was over 10°F, but at 60 cm was only about 4°F (Figure 5; Figure 6). The treatment site had a lower temperature reading than the control site from the evening to about midday every day. The control site had a lower recorded temperature than the treatment site during times of maximum daily temperature. At both heights, the magnitudes of peak differences where the control recorded temperature is lower and where the treatment recorded temperature is lower in a single day are about the same and range from moderate to substantial at 0 cm, and minimal to moderate at 60 cm.

Because there was no significant difference between the control sensors at 0 and 60 cm but there was a significant difference between the treatment sensors at 0 and 60 cm heights, it is likely that the bioretention cell is mainly functioning to mitigate high temperatures at a near-ground level, but the effect lessens with higher elevations. This shows that the effect of the SCM on air temperature changes spatially and decreases with distance from the soil. Due to the control site having a lower recorded temperature than the treatment site during the peak temperature times of the day, Canyon does not effectively mitigate the UHI effect compared to its control. This is surprising because Canyon is a fairly large regional bioretention cell, but the control was placed over a grassy area. It is possible that shading from surrounding trees at the treatment and control sites could differ between sites during peak afternoon hours and thus affect temperature readings at each site differently.

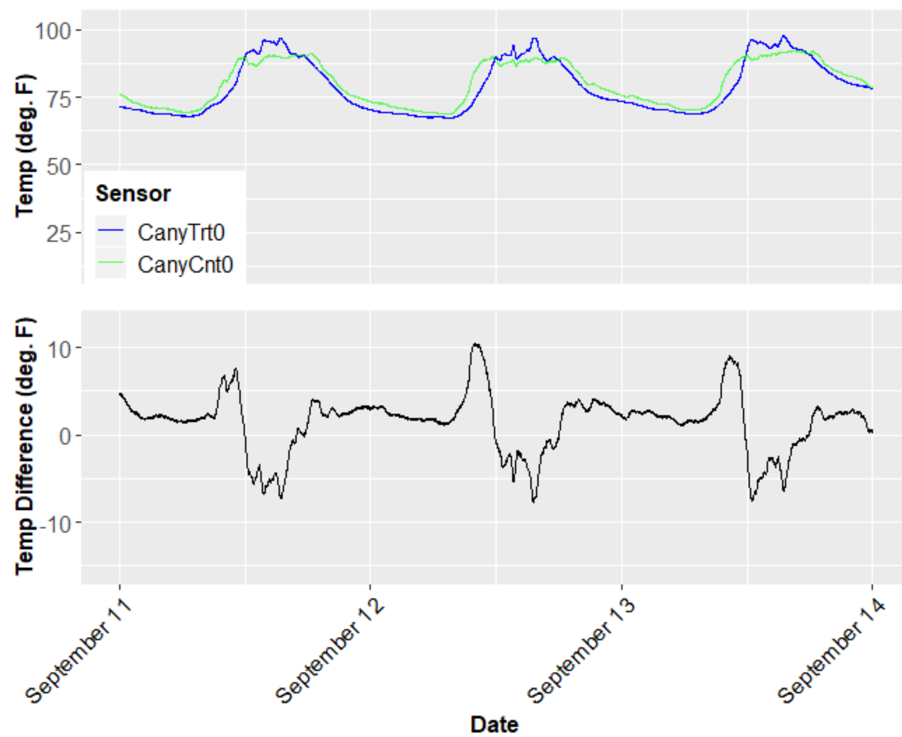


Figure 5. Temperature difference between treatment and control sites at 0 cm at Canyon from September 11-13, 2019. A positive difference indicates that the control site had a higher temperature reading than the treatment site.

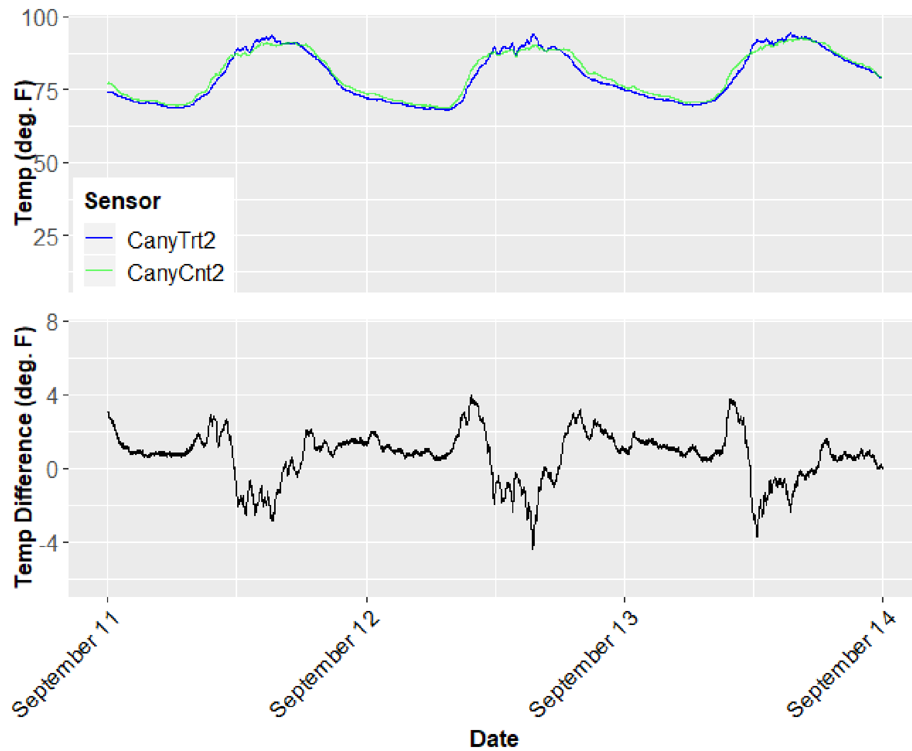


Figure 6. Temperature difference between treatment and control sites at 60 cm at Canyon from September 11-13, 2019. A positive difference indicates that the control site had a higher temperature reading than the treatment site.

Front

Upon further analysis it was determined that the maximum temperature difference of 18.53 °F in August was an anomaly as temperature differences for the rest of August and September do not reach above 5°F (Figure 7). On August 26, 2019, the day this extreme temperature difference occurred, the recorded temperature was abnormally low for August as it did not reach above 70°F. Because this air temperature is not extreme and does not raise concern for UHI effects, this day will not be considered further, and the difference is considered an outlier as no other difference near to this magnitude was recorded at Front.

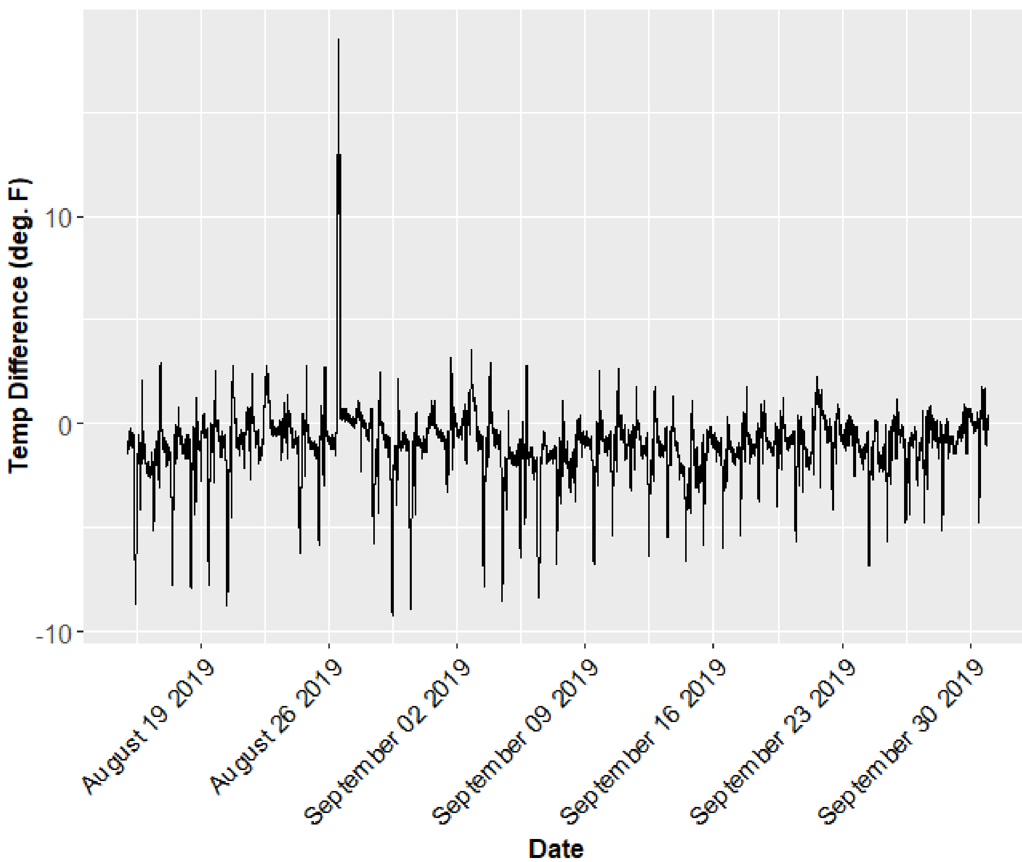


Figure 7. Temperature differences between treatment and control at 0 cm at Front from mid-August to October. A positive difference indicates the control site had a higher temperature reading than the treatment site.

At Front, there were more moderate differences at 60 cm than 0 cm, but overall, the moderate and substantial temperature differences were low in duration when compared to Canyon (Table 9). Less than 10 hours of moderate temperature differences existed at this site across an approximately 5160-hour monitoring period.

Table 9. Duration of Temperature Difference Classifications at Front at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	**Duration Temperature Difference Occurred (hours)**	
	0 cm Height	**60 cm Height**
Moderate (3-8 °F)	1.7	5.3
Substantial (>8 °F)	0	0

In examining the period from September 11-13, 2019 at 60 cm, the control site often had a lower recorded temperature than the treatment site, especially around midday when most people would be active and experiencing the outdoor air temperature (Figure 9). At 0 cm, the differences had similar trends but lower magnitudes (Figure 8). The peak differences when the treatment site had a lower recorded temperature than the control correspond with the maximum temperature of the day, but the peak temperature differences are minimal (i.e., <3°F).

Due to the very low durations of moderate temperature difference, the design of the bioretention cell at Front should not be considered adequate for mitigating the UHI effect. Because the bioretention cell is relatively small, encased in concrete, and surrounded by concrete pavement (see Table 1 and Appendix A), it is likely not sufficient for mitigating high temperatures as the minimal vegetative area would not be enough to compensate for the contributions of the surrounding low albedo infrastructure. This suggests that bioretention cells in ultra-urban locations, which tend to have small surface areas, may not mitigate the UHI.

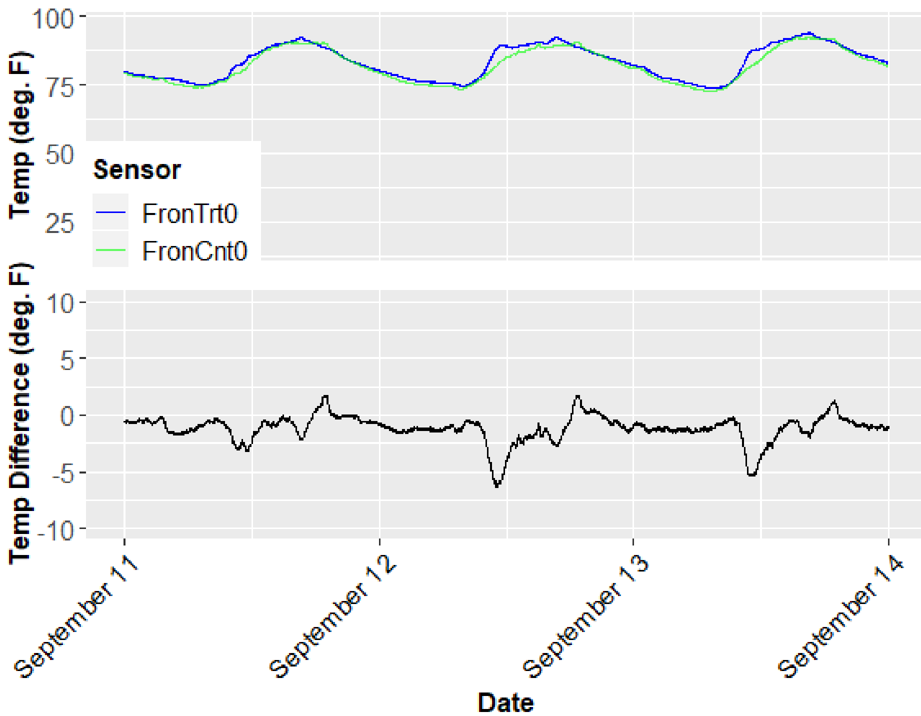


Figure 8. Temperature differences between treatment and control sites at 0 cm at Front from September 11-13, 2019. A positive difference indicates that the control site had a higher temperature reading than the treatment site.

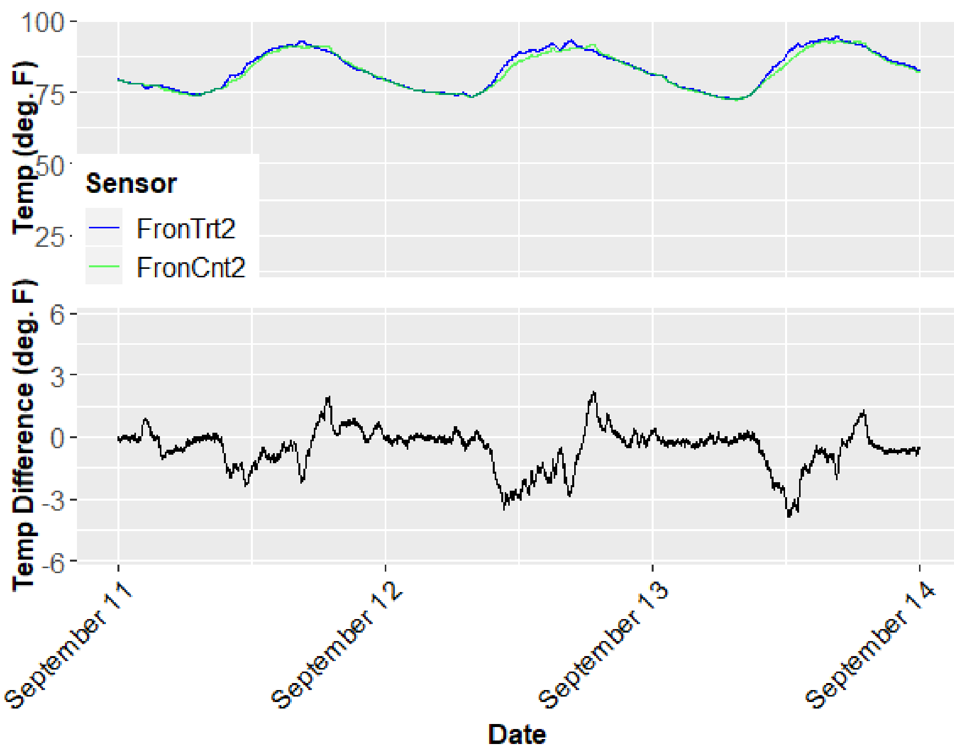


Figure 9. Temperature differences between treatment and control sites at 60 cm at Front from September 11-13, 2019. A positive difference indicates that the control site had a higher temperature reading than the treatment site.

Glenmont

Glenmont had over 100 and 1000 hours of substantial and moderate temperature differences at 0 cm, respectively (Table 10). The duration of substantial (5 hours) and moderate (806 hours) was reduced at the 60 cm height.

Table 10. Duration of Temperature Difference Classifications at Glenmont at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	1067	806
Substantial (>8 °F)	111.5	5

In analyzing the period from September 11-13, 2019, at 0 cm the treatment sensor almost always had a lower temperature measurement than the control with differences up to almost 10°F (Figure 10). There are, however, some peak afternoon temperatures that are, for a short duration, hotter at the treatment site than at the control. This may be related to the timing of the peak temperatures. Concrete and asphalt heat and cool more quickly than a vegetated SCM surface. Thus, as the sun sets, the road cools more quickly than the bioretention cell, resulting a short window of time where the bioretention cell is actually hotter than the control site. However, at the 60 cm height, the maximum differences were significantly lower, and the control had a lower recorded temperature than the treatment site for longer periods of the day (Figure 11). In general, the maximum temperature recorded in the day coincided with the control site having a lower recorded temperature than the treatment site with the difference ranging from minimal to moderate. The maximum temperature difference when the treatment site had a lower recorded temperature than the control was moderate.

It is difficult to determine if the UHI effect is mitigated at the site as it seems that the control site has a lower temperature than the treatment site during peak temperature durations that worsens with an increase height. Because there was a statistical difference between the treatment sensors at 0 and 60 cm heights but there was no statistical difference between the control sensors at 0 and 60 cm heights, it is likely that the bioretention cell is mainly functioning to mitigate high temperatures at a near-ground level, but the effect lessens with higher elevations. Glenmont has better results than Front likely due to the fact that it is a larger bioretention cell in a suburban rather than ultra-urban environment (see Table 1). The results at Glenmont are similar to Canyon but with slightly longer periods of the treatment site having a lower temperature than the control.

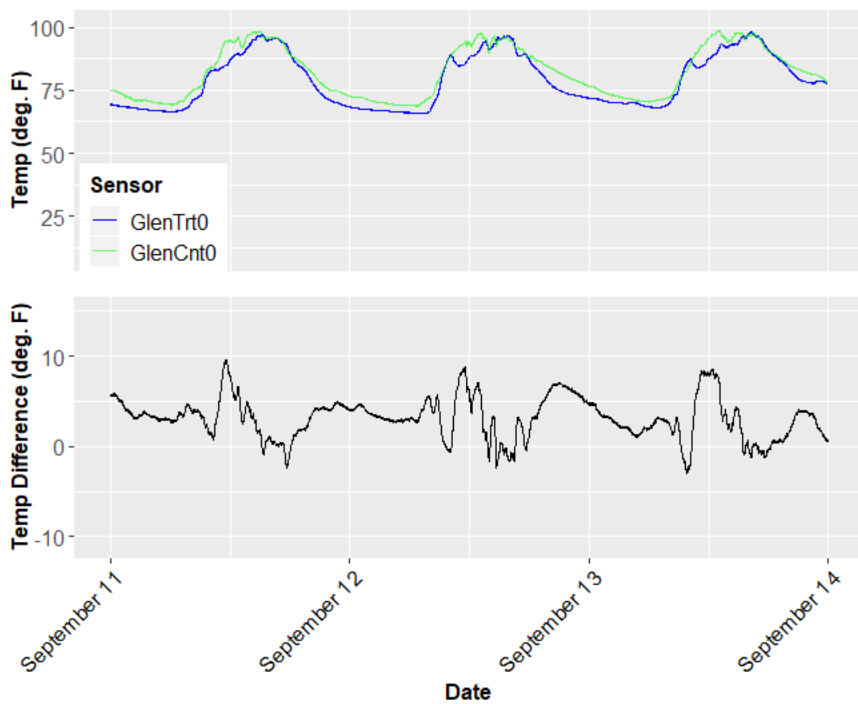


Figure 10. Difference between control and treatment sites at 0 cm at Glenmont from September 11-13, 2019. A positive difference indicates the control site had a higher temperature reading than the treatment site.

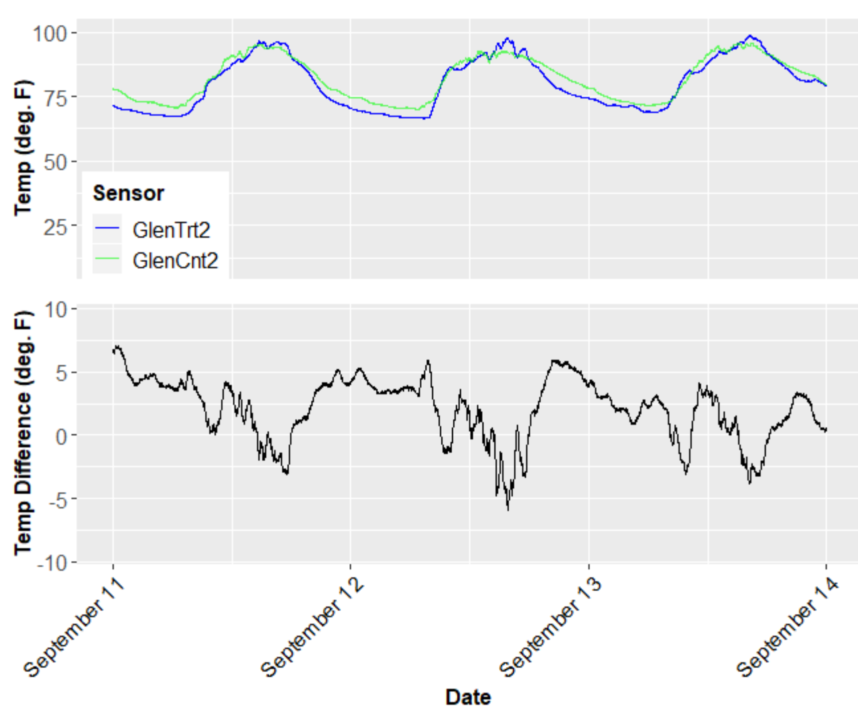


Figure 11. Temperature difference between treatment and control at 60 cm at Glenmont from September 11-13, 2019. A positive difference indicates the control site had a higher recorded temperature than the treatment site.

Main

There was not a major difference between the temperature difference classification durations between treatment and control sites at 0 and 60 cm (Table 11). In fact, moderate temperature differences between control and treatment occurred over a greater period at the 60 cm height.

Table 11. Duration of Temperature Difference Classifications at Main at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	463	505
Substantial (>8 °F)	2.7	1

In analyzing the period from September 11-13, 2019, the 0 cm and 60 cm heights had very similar temperature difference trends and magnitudes (Figure 12; Figure 13). The treatment site at Main almost always had a lower temperature reading than the control site. The instances in which the control site did have a lower temperature reading than the treatment site were during minimal temperatures for the day that occurred in the morning for very short periods of time. The differences were minimal whereas the treatment site had a moderately lower temperature reading than the control site for the rest of the day, peaking around the time of maximum temperature.

Main contributes considerably to the mitigation of the UHI effect. This result is interesting as Front, which has a very similar design to Main but is slightly smaller, did not contribute to UHI effect mitigation. It is possible that the shading from buildings at Front and Main differed throughout the day which could lead to the disparity among differences between the sites at the different locations.

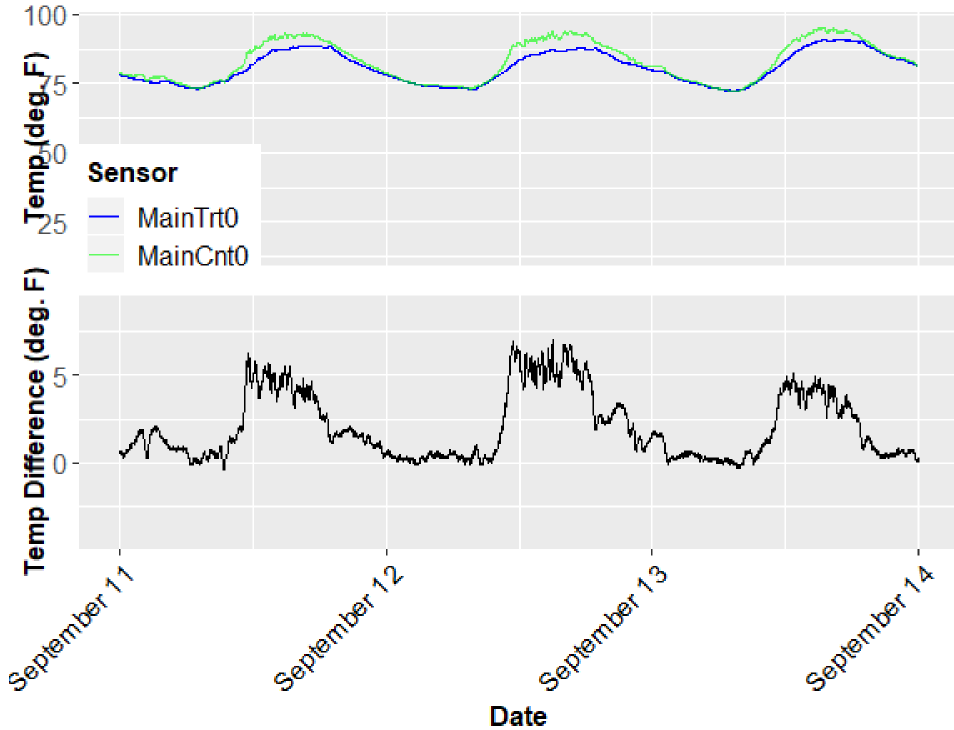


Figure 12. Temperature difference between treatment and control sites at 0 cm at Main from September 11-13, 2019. A positive difference indicates the control site had a higher temperature reading than the treatment site.

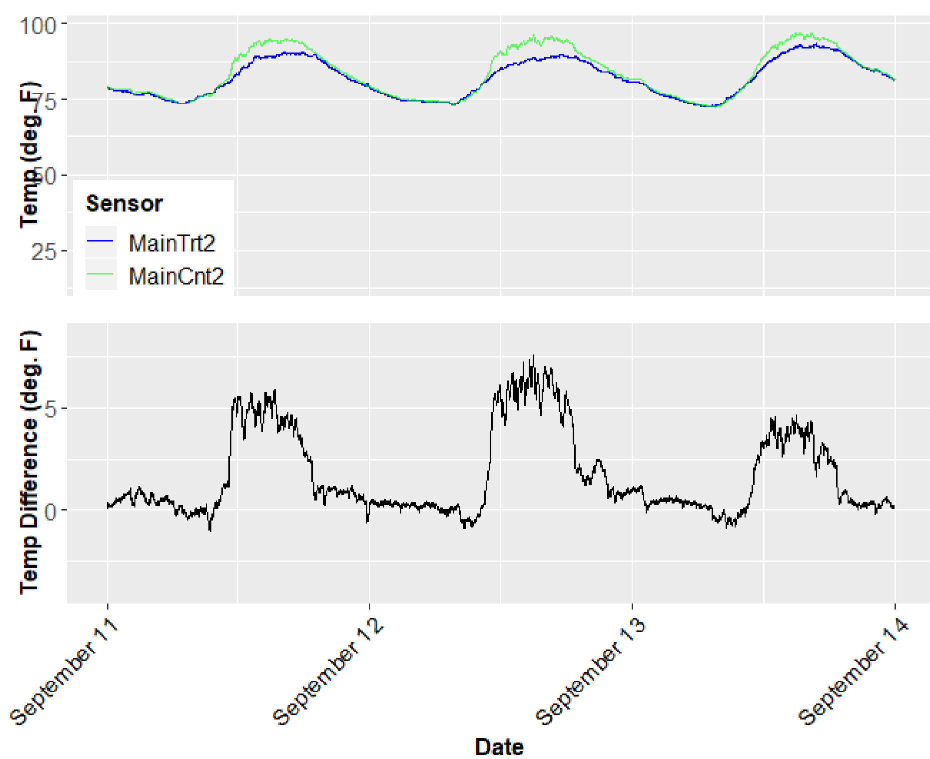


Figure 13. Temperature differences between treatment and control sites at 60 cm at Main from September 11-13, 2019. A positive difference indicates the control site had a higher recorded temperature than the treatment site.

Star

Star had more moderate and substantial temperature differences at 0 cm than at 60 cm, but very few substantial temperature differences overall (Table 12). Star was located adjacent to a moderate traffic road, and the bioretention cell was approximately 50 ft away from the road. This is dissimilar to the other bioretention cells studied herein, which tended to directly abut the street.

Table 12. Duration of Temperature Difference Classifications at Star at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	567	315
Substantial (>8 °F)	4.6	0

In analyzing the period from September 11-13, 2019, the 0 cm and 60 cm heights had very similar temperature difference trends and magnitudes (Figure 14; Figure 15). The control site had lower recorded temperatures than the treatment site for much of the day, peaking a little after midday where the daily temperature peaked as well. It appears the treatment site only had lower temperatures readings than the control site from early evening until early morning.

Because the peak differences were only moderate for a few of the hottest days of the year and the control experiences a lower temperature than the treatment site for much of the daytime hours, Star is not considered ideal for mitigating the UHI effect. However, it is important to note that at the treatment site, the sensors were over bare soil within the bioretention cell, and the control sensors were over a grassy area. Most of the vegetation was taller than 60 cm at the treatment site, therefore it would be beneficial for future research to see the temperature difference at maybe 1.2 or 1.5 m.

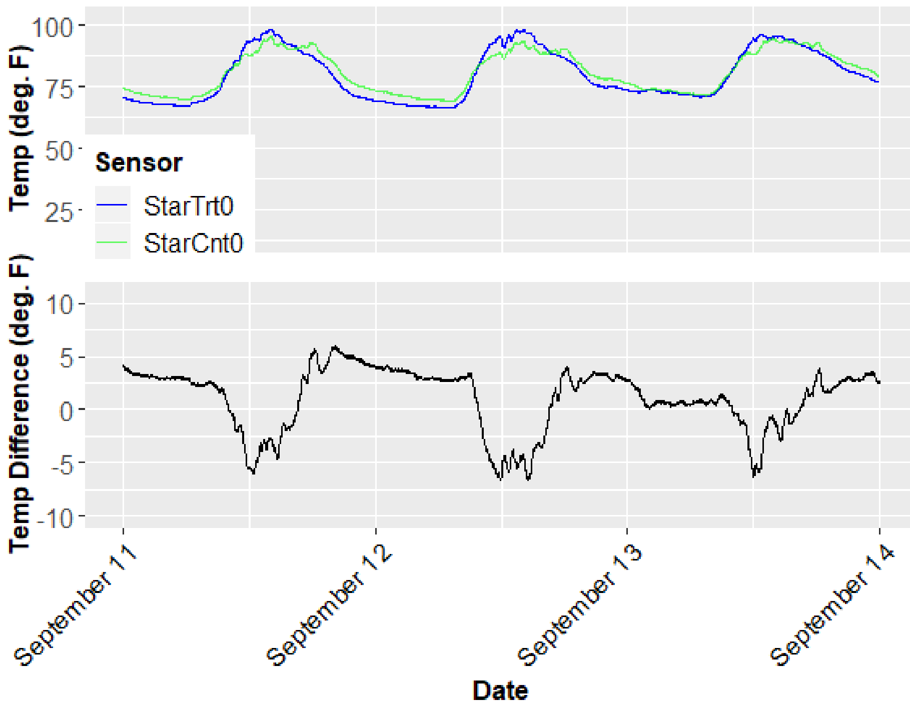


Figure 14. Temperature difference between treatment and control sites at 0 cm at Star from September 11-13, 2019. A positive difference indicates the control site had a higher temperature reading than the treatment site.

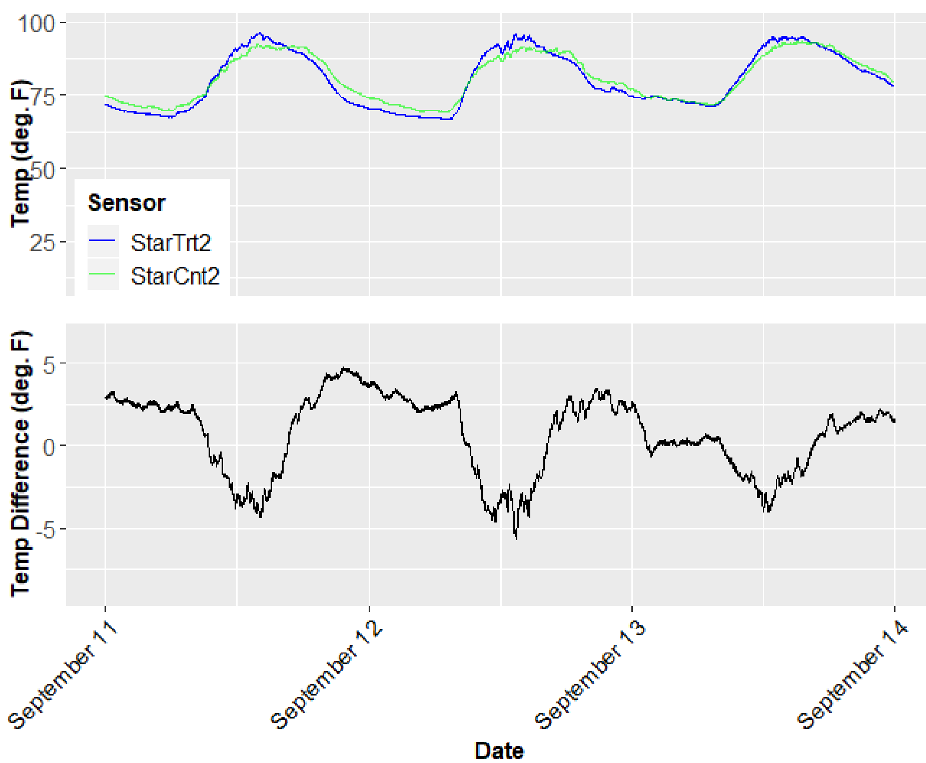


Figure 15. Temperature differences between treatment and control sites at 60 cm at Star from September 11-13, 2019. Positive differences indicate the control site had a higher temperature reading than the treatment site.

Green Roofs

All the green roof locations had a significant difference between the control and treatment sites at 0 and at 60 cm aside from 0 cm at Knowlton and 60 cm at Audubon. At Howlett and Whetstone, all the average differences between the treatment and control sensors at both heights were positive, indicating that the significant difference between treatment and control likely corresponded to the treatment site having lower temperatures than the control site. Lazarus had a positive average difference at 0 cm through December and at 60 cm through July. Knowlton had a positive average difference at both heights for all months recorded aside from August at 0 cm. The average differences at Audubon varied highly, with 0 cm having positive average differences every month data was recorded aside from July whereas 60 cm had negative average differences from June to August and October. In the following sections, all the green roof locations (Audubon, Howlett, Knowlton, Lazarus, and Whetstone) will be analyzed to see how many days moderate and substantial temperature differences between the treatment and control sites occurred, when those differences likely occurred in the day, and how site characteristics may have contributed to the results.

Audubon

Audubon had more substantial temperature differences between treatment and control at 60 cm than at 0 cm, but similar moderate temperature differences at both heights. This result is unexpected as the paired t-test results showed that there was no significant difference between the treatment and control at 60 cm. There were also extreme temperature differences recorded for 60 cm at Audubon, with the treatment measuring up to 22°F cooler than the treatment in September and the control measuring up to 31°F warmer in October.

Table 13. Duration of Temperature Difference Classifications at Audubon at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	480	411
Substantial (>8 °F)	59	185

Unfortunately, there was an issue with the treatment 0 cm sensor and data was not recorded throughout the entirety of August, September, and most of October. Therefore, the 60 cm height was analyzed during these dates and both sensor heights were analyzed from July 19-21, 2019 as all sensors at Audubon were functioning during these dates and temperatures in Columbus reached over 90°F.

The treatment site only had a lower temperature reading than the control from the evening to early morning on the first few days, until September 13th when the treatment temperature exceeded the control from very early morning until the middle of the night when the chosen period ends (Figure 16). Midday September 13th, the treatment site was over 20°F warmer than the control site. It is unclear why this difference occurred as there was no recorded precipitation or other anomaly on this day. The temperature on the 13th was very similar to the 11th and 12th.

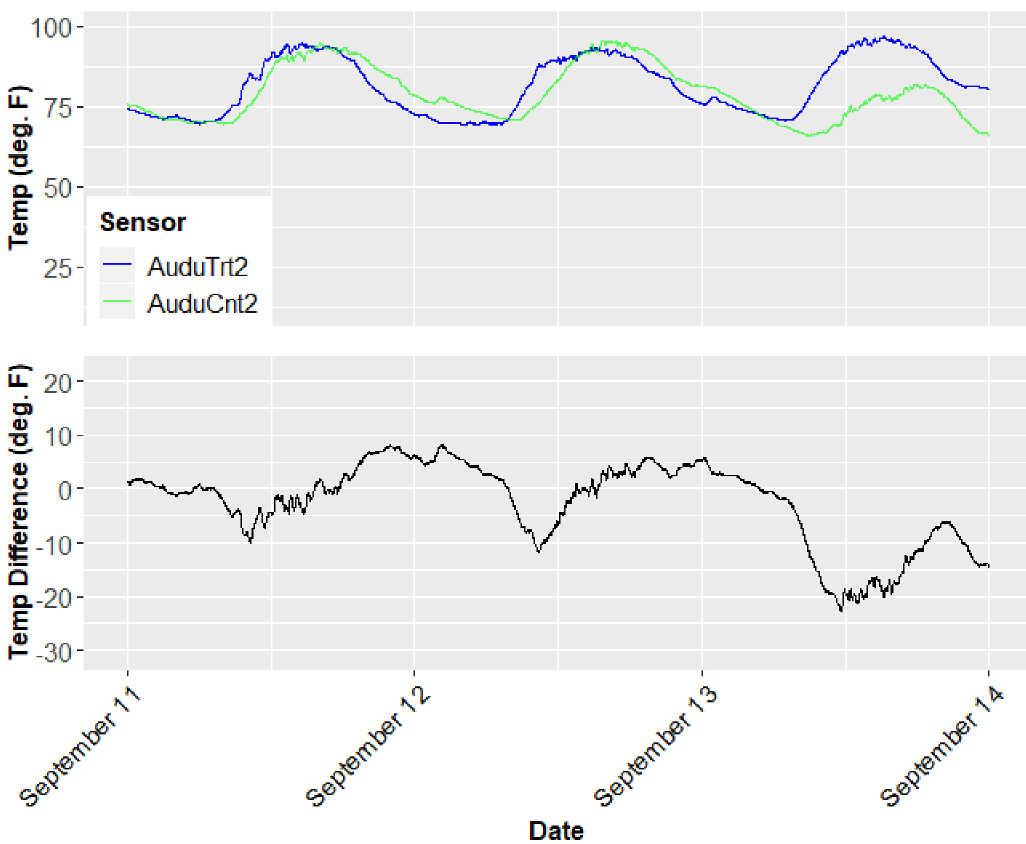


Figure 16. Temperature differences between treatment and control sites at 60 cm at Audubon from September 11-13, 2019. Positive differences indicate the control site had a higher temperature reading that the treatment site.

From July 19-21, 2019, the differences between treatment and control sites were minimal to moderate aside from late afternoon July 21st at 0 cm where the control site measured over 10°F less than the treatment site (Figure 17). There was recorded precipitation on July 21, 2019 which may indicate that the control roof better mitigates the UHI effects during precipitation events than the green roof. These results are interesting at 60 cm, as the temperatures recorded from

September 11-13, 2019 were very similar, but the magnitude and trends of the differences are different from July 19-21, 2019 (Figure 18). It is unclear what may contribute to this difference in trends across different time periods.

Because the control site had lower temperatures than the treatment site during the day in the September time period with large magnitude at some points and minimal to low-moderate differences were observed in the July time period, the green roof design as Audubon does not mitigate the UHI effect more than the white roof it was compared to as a control.

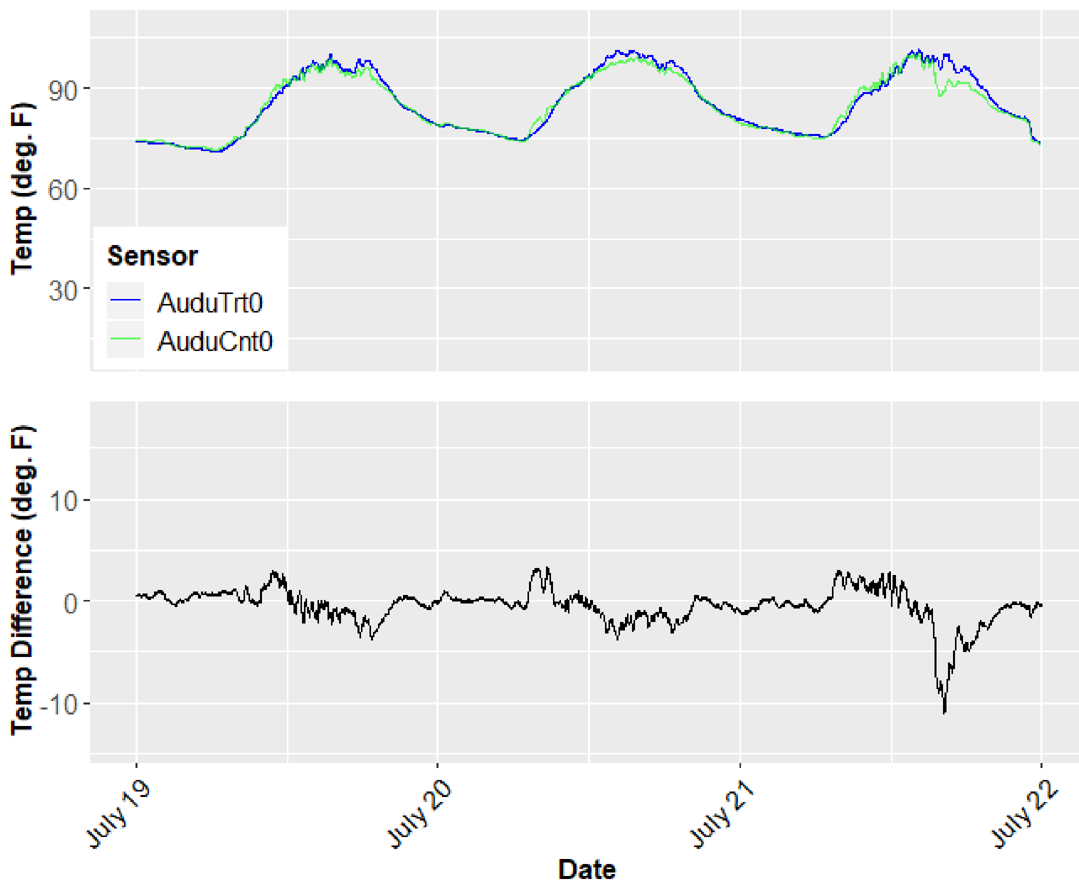


Figure 17. Temperature difference between treatment and control sites at 0 cm at Audubon from July 19-21, 2019. Positive differences indicate the control site had a higher recorded temperature than the treatment site.

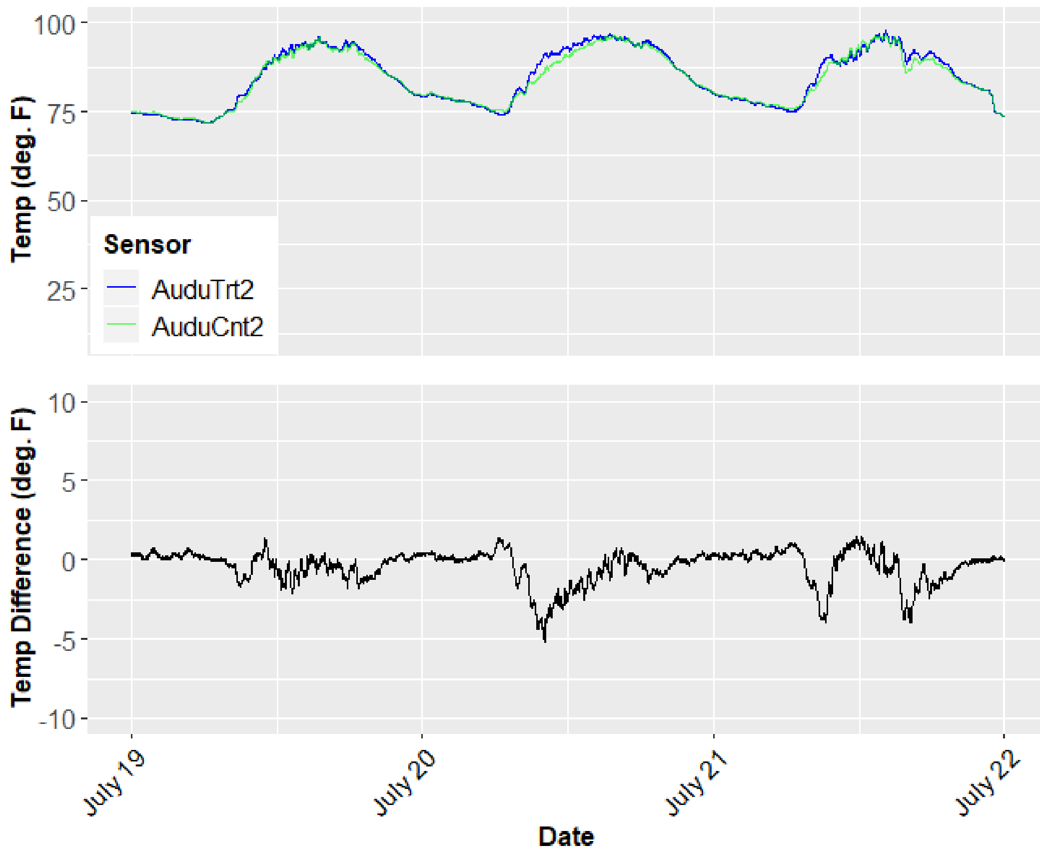


Figure 18. Temperature differences between treatment and control sites at 60 cm at Audubon from July 19-21, 2019. Positive differences indicate the control site had a higher temperature reading than the treatment site.

Howlett

Howlett had about the same duration of substantial temperature differences at 0 and 60 cm, but much more moderate temperature differences at 0 cm than at 60 cm.

Table 14. Duration of Temperature Difference Classifications at Howlett at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	352	133
Substantial (>8 °F)	4.7	4.2

Because there was no data collected during the September 11-13, 2019 time period, the July 19-21, 2019 time period was analyzed at the Howlett green roof. The temperature differences between treatment and control at 0 cm had greater magnitudes than at 60 cm. At 0 cm, the treatment site had a lower temperature than the control site only from the evening until morning the next day (Figure 19). During the peak daily temperature, the control site had a lower temperature reading than the treatment site, ranging from moderate to near substantial. At 60 cm, the differences between treatment and control were minimal except for July 21st when the treatment site was over 5°F cooler than the control site around midday (Figure 20). There was recorded precipitation on July 21, 2019, therefore it is likely that precipitation during high temperature events improves effectiveness of UHI effect mitigation by the green infrastructure design at Howlett. The precipitation is likely to cool the green roof, but also would cool the control roof so increase effectiveness may be due to longer retention times of the water on the green roof or more evapotranspiration.

Because the control site had lower temperature readings for most of the day at 0 cm and the temperature differences were mostly minimal at 60 cm, Howlett is not considered able to mitigate the UHI effect compared to its control, a white roof, during days without precipitation. However, on days with high temperatures and precipitation, Howlett had a moderate effect on UHI effect mitigation.

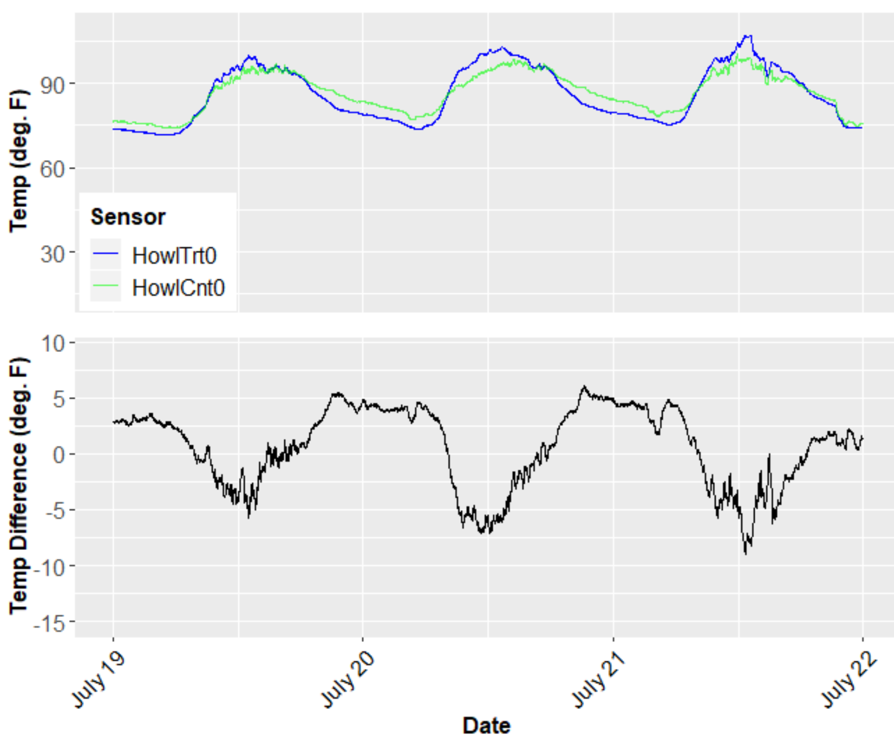


Figure 19. Temperature differences between control and treatment sites at 0 cm at Howlett from July 19-21, 2019. A positive difference indicates the control site had a higher temperature reading than the treatment site.

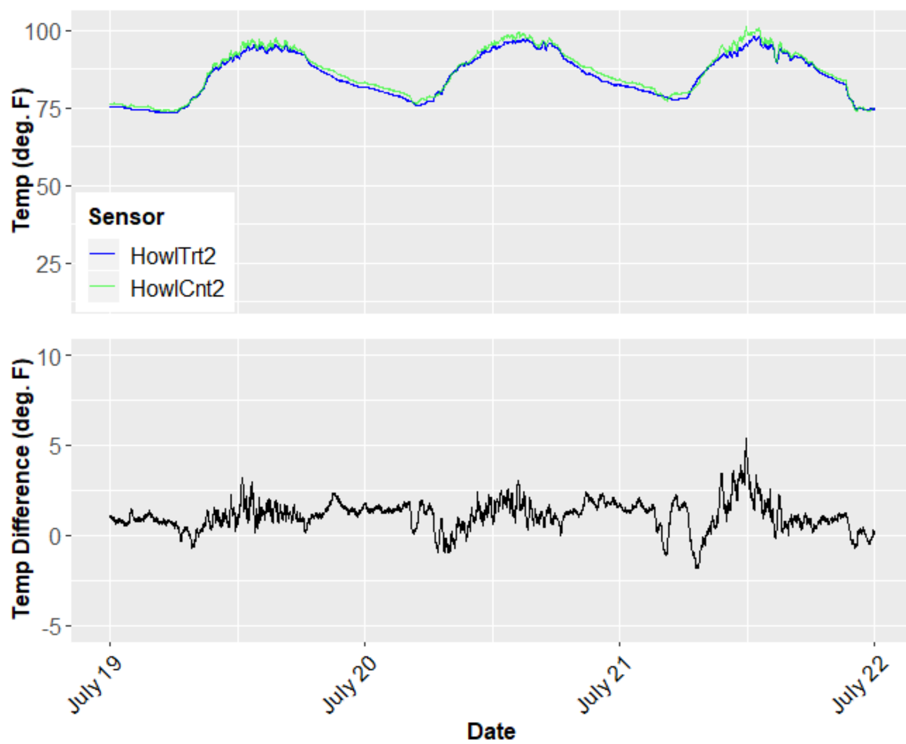


Figure 20. Temperature differences between treatment and control sites at 60 cm at Howlett from July 19-21, 2019. A positive difference indicates the control site had a higher temperature reading than the treatment site.

Knowlton

At Knowlton the duration of moderate and substantial temperature differences between treatment and control sites at 0 and 60 cm were less than 10% different (Table 15).

Table 15. Duration of Temperature Difference Classifications at Knowlton at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	119	131
Substantial (>8 °F)	9.8	9.4

Data was not collected at Knowlton for the September 11-13, 2019 time period so the July 19-21, 2019 time period was analyzed instead. The trends and magnitudes of temperature differences between treatment and control were very similar; because there was no statistical difference between the treatment and control sites at 0 cm, the 60 cm height will be discussed further. During a large portion of the day, the treatment site had a minimally to substantially lower temperature reading compared to the control site (Figure 21). The treatment site had substantially lower temperature readings than the control on July 21, 2019, a day when precipitation was recorded, during the maximum temperature of the day. However, there was an instance in late afternoon when the control had a minimally lower temperature reading than the treatment site.

Knowlton somewhat able to mitigate the UHI effect compared to its traditional roof control due to the treatment site having a lower temperature reading than the control for a large majority of the day, with efficacy increasing for the most part during precipitation events. Knowlton may have a better effect than Audubon and Howlett because it is a highly intensive green roof with tall vegetation and was compared to a traditional black roof whereas Audubon and Howlett were compared to white roofs (Table 1).

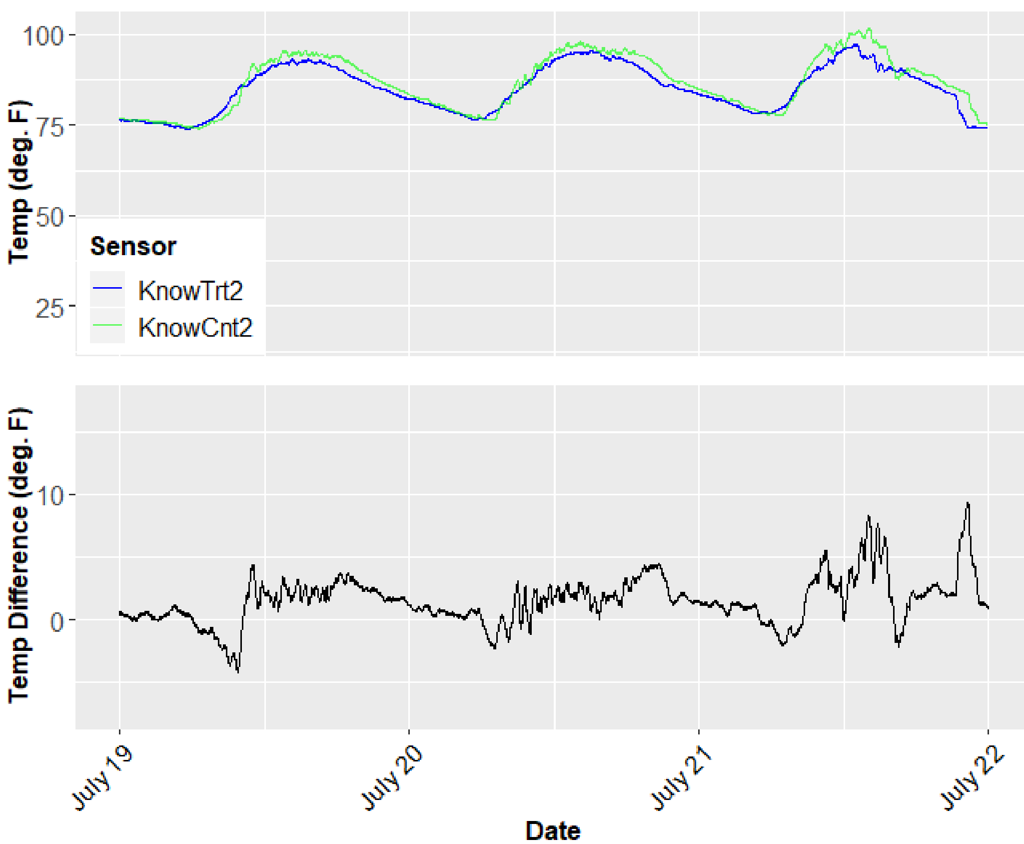


Figure 21. Temperature difference between treatment and control sites at 60 cm at Knowlton from July 19-21, 2019. Positive difference indicates the control site had a higher temperature reading than the treatment site.

Lazarus

Lazarus exhibited a much longer duration of moderate temperature differences between treatment and control at 0 cm than at 60 cm (Table 16). Only 5.2 hours of substantial temperature differences were observed at ground level, while substantial temperature differences were not observed at 60 cm.

Table 16. Duration of Temperature Difference Classifications at Lazarus at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	386	4.9
Substantial (>8 °F)	5.2	0

Data was recorded at Lazarus during both the September 11-13, 2019 and July 19-21, 2019 time periods. Precipitation did not appear to have an effect on air temperature at Lazarus; therefore, the September 11-13, 2019 dates were analyzed. Similar temperature trends occurred at 0 and 60 cm, but the magnitude of the differences was greater at 0 cm (Figure 22; Figure 23). The treatment site had a lower temperature reading than the control site from a little after midday until early morning the next day at both heights. At 0 cm, the maximum differences were minimal to low-moderate whereas the differences were minimal at 60 cm. The control site had a lower temperature than the treatment site when temperature was increasing throughout the day, but around when the daily temperature reached its peak, the treatment site had lower temperatures than the control.

Because of the relatively low temperature differences, Lazarus is only somewhat considered able to mitigate the UHI effect compared to its traditional control roof. The control roof for Lazarus was a traditional dark-colored roof and the area of the green roof at Lazarus is rather large (Table 1) which may explain why better results were obtained at Lazarus compared to Audubon and Howlett that had white roof controls.

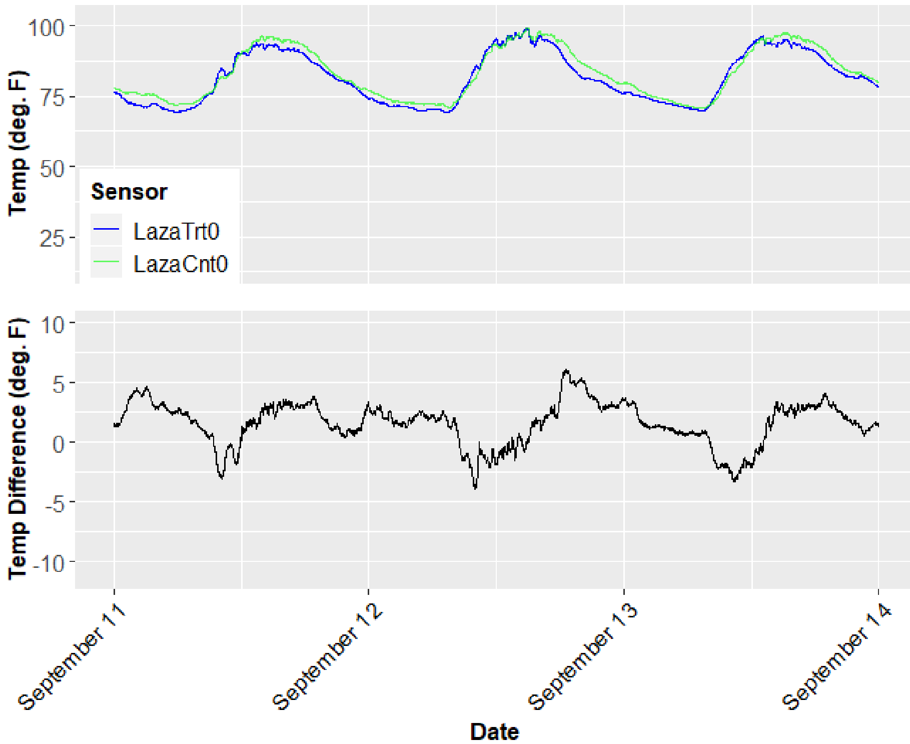


Figure 22. Temperature difference between treatment and control at 0 cm at Lazarus from September 11-13, 2019. Positive difference indicates that the control site had a higher temperature reading than the treatment site.

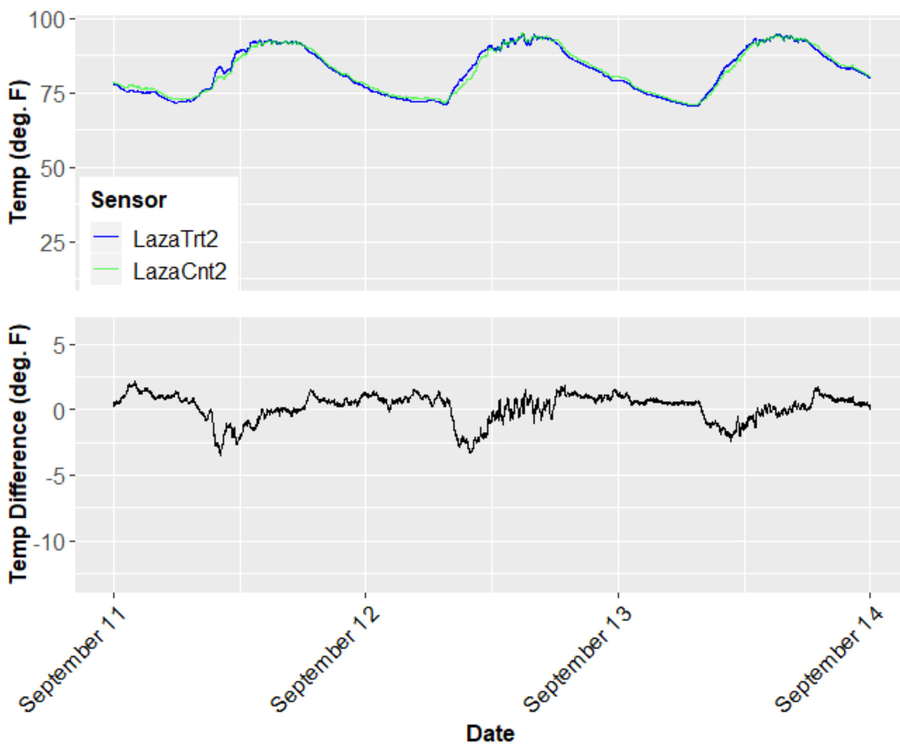


Figure 23. Temperature difference between treatment and control sites at 60 cm at Lazarus from September 11-13, 2019. Positive difference indicates the control site had a higher temperature reading than the treatment site.

Whetstone

Whetstone had a greater duration of moderate temperature differences between treatment and control at 60 cm than at ground level (Table 17). Greater durations of substantial temperature differences occurred at 0 cm.

Table 17. Duration of Temperature Difference Classifications at Whetstone at 0 cm and 60 cm Sensor Heights

Temperature Difference Classification	Duration Temperature Difference Occurred (hours)	
	0 cm Height	60 cm Height
Moderate (3-8 °F)	457	584
Substantial (>8 °F)	32	0.6

Data was not recorded at Whetstone until August, therefore only the September 11-13, 2019 time period will be analyzed in detail. The magnitudes and patterns of temperature differences between treatment and control sites at 0 and 60 cm were very different. At 0 cm, the treatment site had a lower temperature than the control site from early morning until about midday and then again in the evening (Figure 24). During the afternoon, when daily temperature was the highest, the temperature difference was very near 0 with minimal fluctuations. However, at 60 cm the treatment site had a moderately lower temperature reading than the control from early morning until late evening and near zero temperature differences during the night with minimal fluctuations (Figure 25).

At Whetstone, the UHI effect is considerably mitigated at 60 cm but not mitigated at 0 cm compared to the white roof control site. Whetstone has low vegetation, similar to Audubon (Table 1), but its control roof was located on a separate part of the building rather than intermixed like Audubon. Whetstone may have been able to mitigate the UHI effect better than Howlett because it is in a more suburban area with surrounding greenspace rather than Howlett which is located on OSU’s campus.

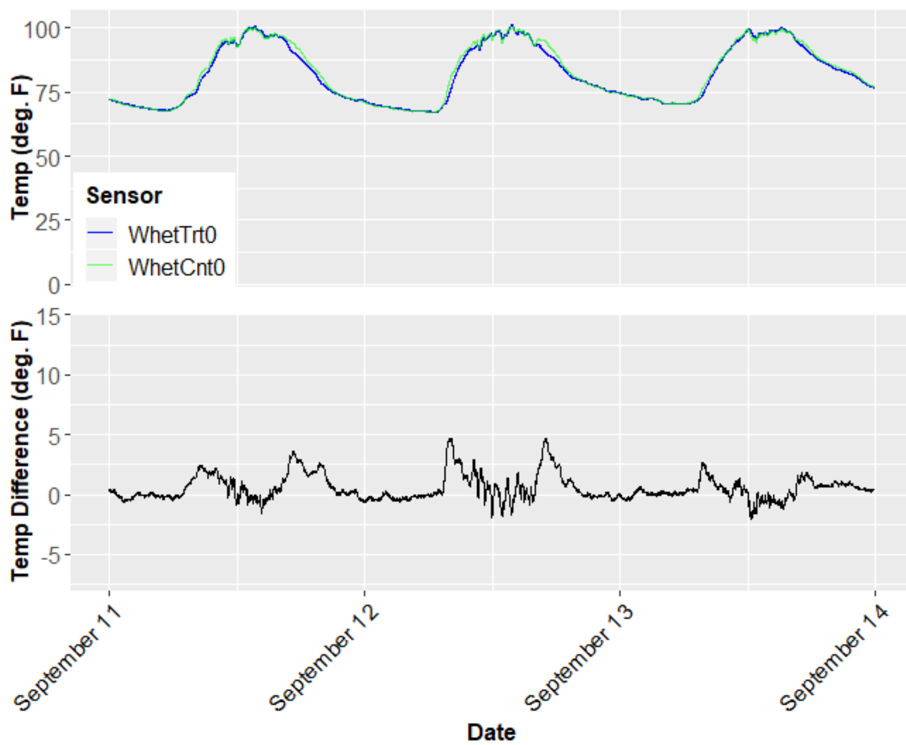


Figure 24. Temperature difference between treatment and control sites at Whetstone at 0 cm from September 11-13, 2019. Positive difference indicates the control site had a higher temperature reading than the treatment site.

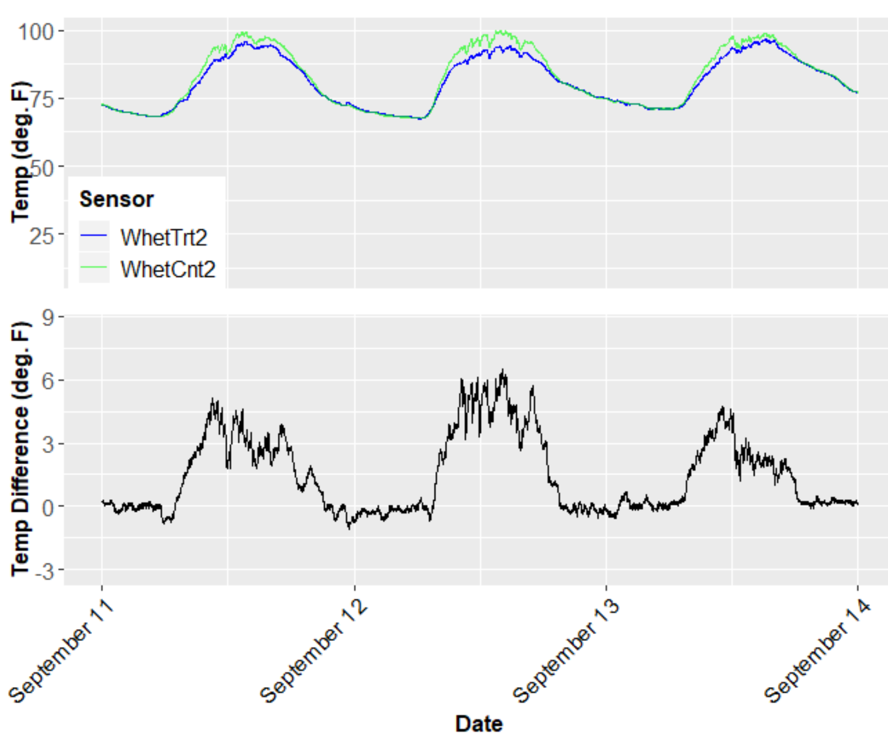


Figure 25. Temperature difference between treatment and control sites at 60 cm at Whetstone from September 11-13, 2019. Positive difference indicates the control site had a higher temperature reading than the treatment site.

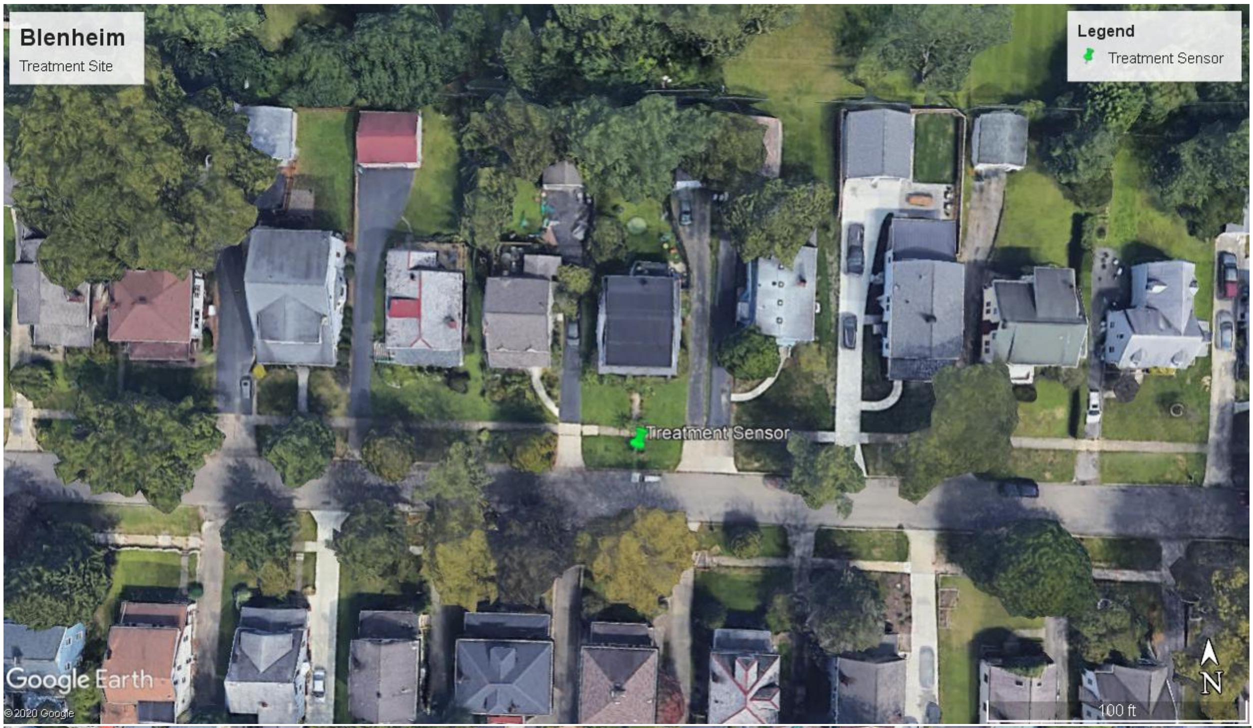
Conclusion

Average temperature differences between treatment and control sites were not an adequate indicator of a site's ability to mitigate the UHI effect. Minimum and maximum temperature differences provide greater insight into how a treatment site's temperature differs compared to a nearby control. However, it was most important to see when the differences between treatment and control sites occurred to determine if the treatment site was mitigating the peak temperature of a day compared to the control during days of extremely high temperatures. Of the bioretention cells analyzed, three were considered not able to mitigate the UHI effect compared to their controls. Main was considered able to mitigate the UHI effect considerably, which is interesting as it had a similar treatment design and control site as Front which was not at all able to mitigate the UHI effect. Shading of treatment and control sites by buildings throughout the day may have contributed to the differing results. Glenmont was somewhat effective at 0 cm, but not at 60 cm compared to its control site which was located over grass. Canyon and Star also had controls over grassy areas but were determined to not have an effect on UHI mitigation. Shading by nearby trees throughout the day may have been a factor in these differing results as Canyon and Star are rather large sites. Of the five green roofs analyzed, two had moderate and one had considerable UHI effect mitigation capacities. Audubon was not considered to have an effect but was compared to a white roof intermixed with the green roof. Howlett was only effective during periods of precipitation when compared to a white roof, so was thus considered not effective overall. Whetstone was considerably effective at 60 cm, but not at 0 cm when compared to a white roof. Therefore, white roofs and green roofs may have similar UHI effect mitigation capacity depending on location; further research is suggested for temperature mitigation at higher elevations above the roof surface. Knowlton and Lazarus both had moderate UHI effect mitigation when compared to traditional, dark-colored roof controls, and Knowlton performed better in precipitation events than dry weather. Green infrastructure design is crucial to assess contribution to UHI effect mitigation but is highly dependent on control comparisons in the nearby area and should be assessed on a case-by-case basis. Bioretention cells, such as Main, and green roofs have the capacity to mitigate the UHI effect to a noticeable degree and thus UHI effect mitigation should be considered as a possible co-benefit.

Appendices

Appendix A. Pictures of Sensor Deployment Sites

Figure 26. Audubon treatment and control sites satellite imagery (top), treatment sensors (bottom left), and control sensors (bottom right).


Blenheim
Treatment Site
Legend
Treatment Sensor
Treatment Sensor
Google Earth
© 2020 Google
N
100 ft

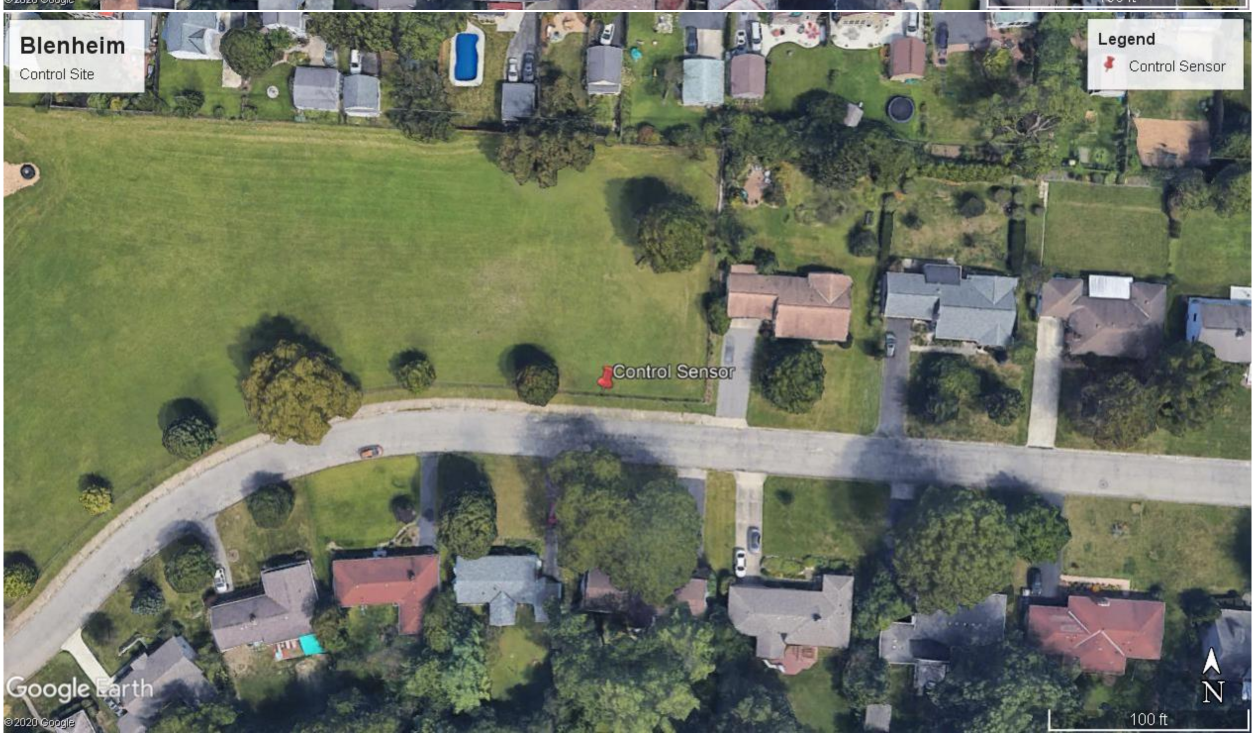

Blenheim
Control Site
Legend
Control Sensor
Control Sensor
Google Earth
© 2020 Google
N
100 ft

Figure 27. Blenheim treatment (top) and control (middle) sites satellite imagery before bioretention installation, treatment sensors (bottom left), and control sensors (bottom right).

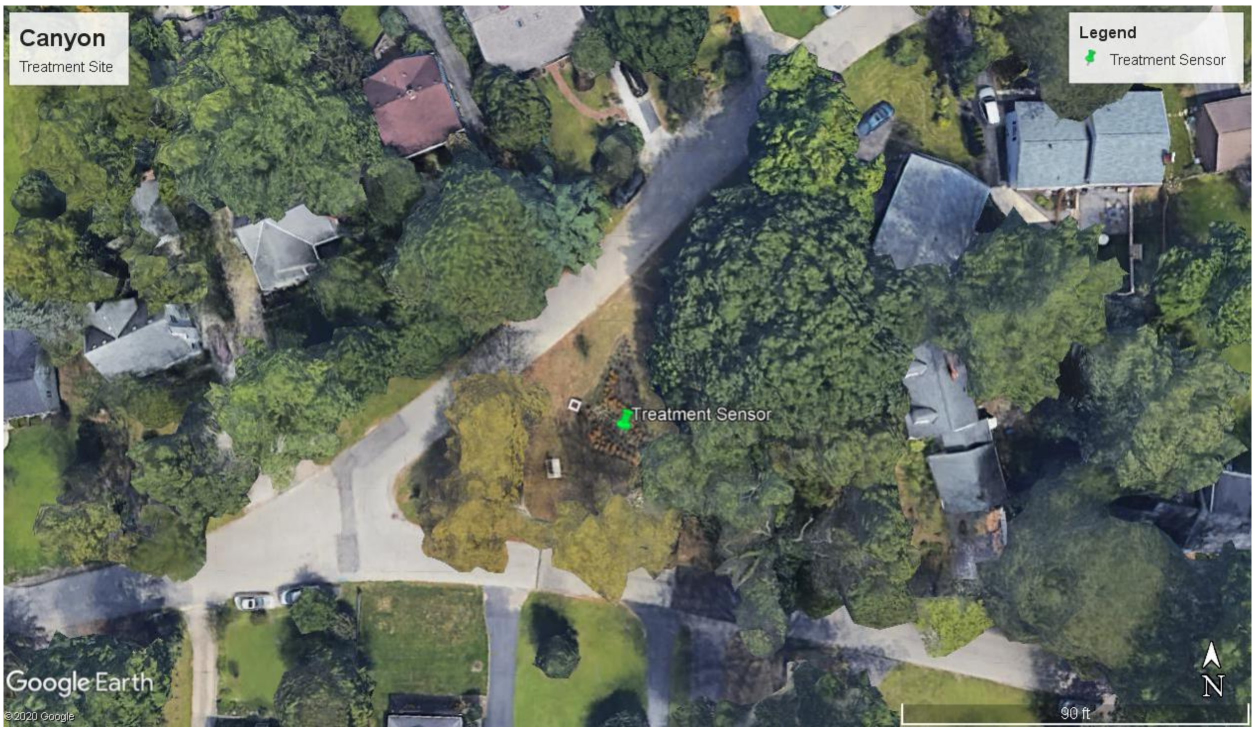
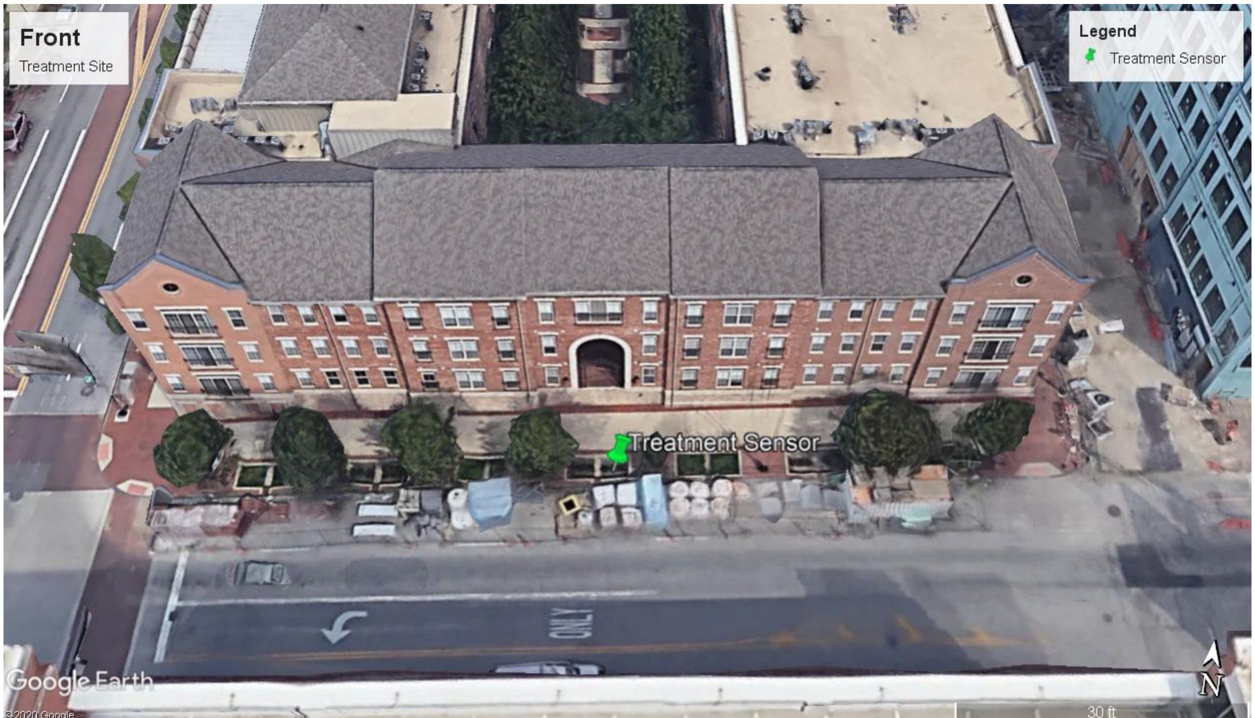


Figure 28. Canyon treatment (top) and control (middle) sites satellite imagery, treatment sensors (bottom left), and control sensors (bottom right).


Front
Treatment Site
Legend
Treatment Sensor
Treatment Sensor
ONLY
Google Earth
© 2020 Google
30 ft


Front
Control Site
Legend
Control Sensor
Control Sensor
Google Earth
© 2020 Google
40 ft

Figure 29. Front treatment (top) and control (middle) sites satellite imagery, treatment sensors (bottom left) and control sensors (bottom right).

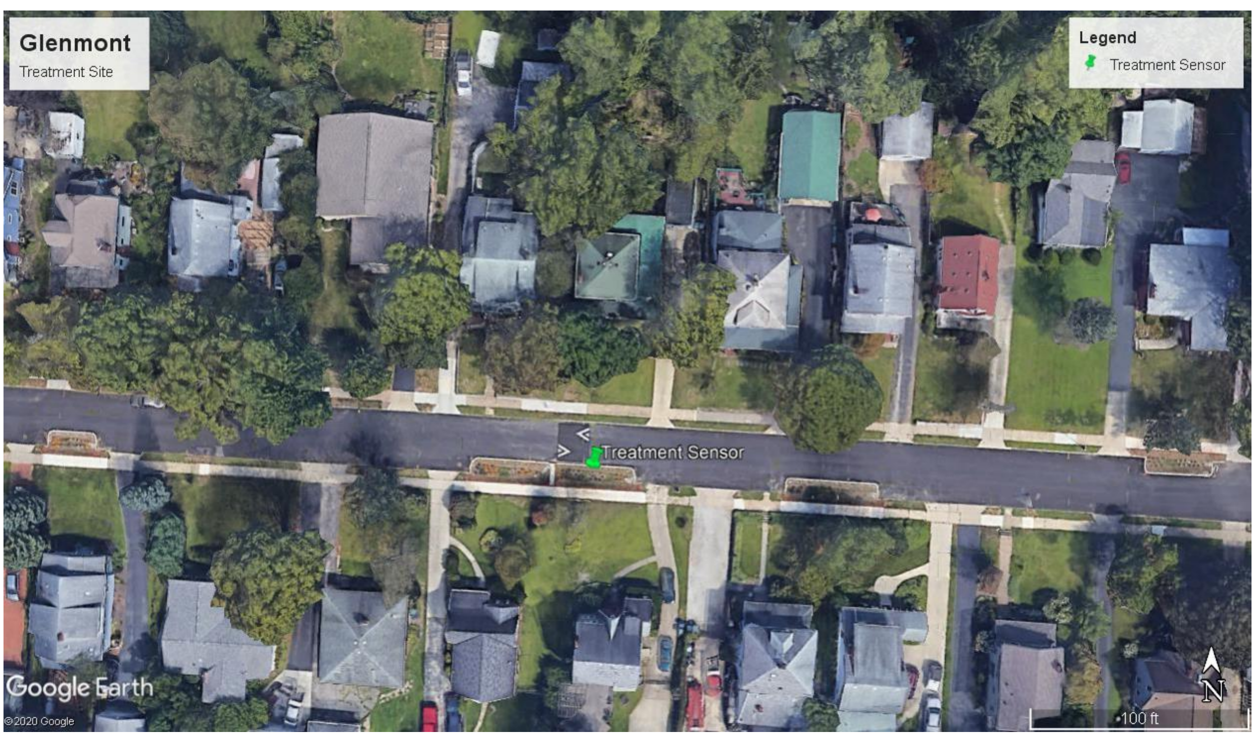


Figure 30. Glenmont treatment (top) and control (middle) sites satellite imagery, treatment sensors (bottom left), and control sensors (bottom right).


Howlett
Treatment Site
Legend
Howlett Hall
Learning Gardens
Treatment Sensor
Woody Hayes Dr & Coffey Rd
Treatment Sensor
Howlett Hall
Google Earth
©2020 Google
100 ft
N


Howlett
Control Site
Legend
Control Sensor
Kottman Hall
Kottman Hall
Control Sensor
Google Earth
©2020 Google
100 ft
N

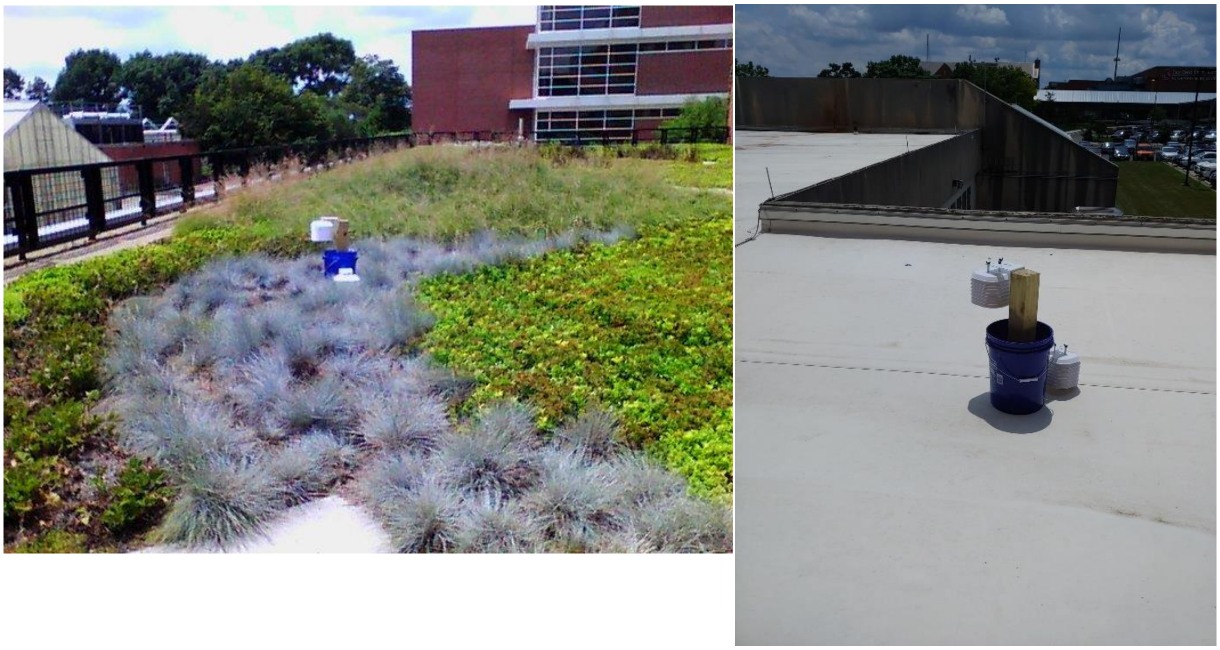
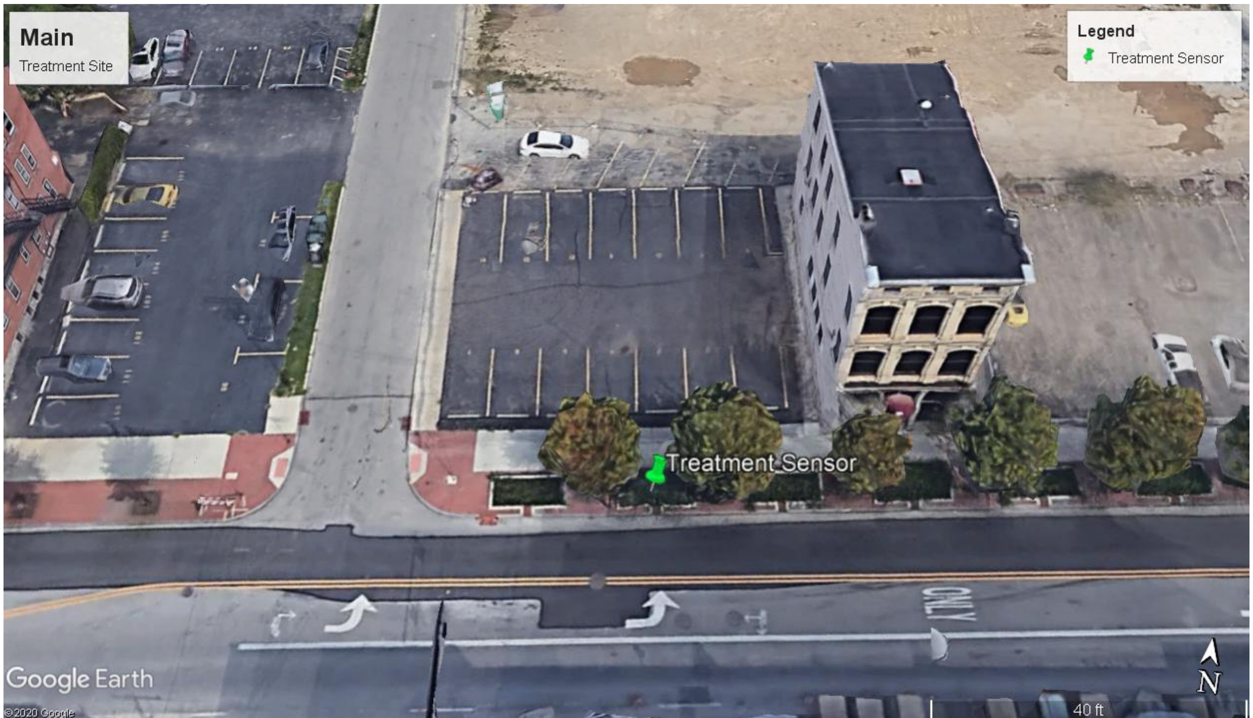


Figure 31. Howlett treatment (top) and control (middle) sites satellite imagery, treatment sensors (bottom left), and control sensors (bottom right).

Figure 32. Knowlton treatment and control sites satellite imagery (top), treatment sensors (bottom left), and control sensors (bottom right).

Figure 33. Lazarus treatment and control sites satellite imagery (top), treatment sensors (bottom left), and control sensors (bottom right).

Figure 34. Library treatment and control sites satellite imagery (top), treatment sensors (bottom left), and control sensors (bottom right).


Main
Treatment Site
Legend
Treatment Sensor
Treatment Sensor
ONLY
Google Earth
© 2020 Google
40 ft
N

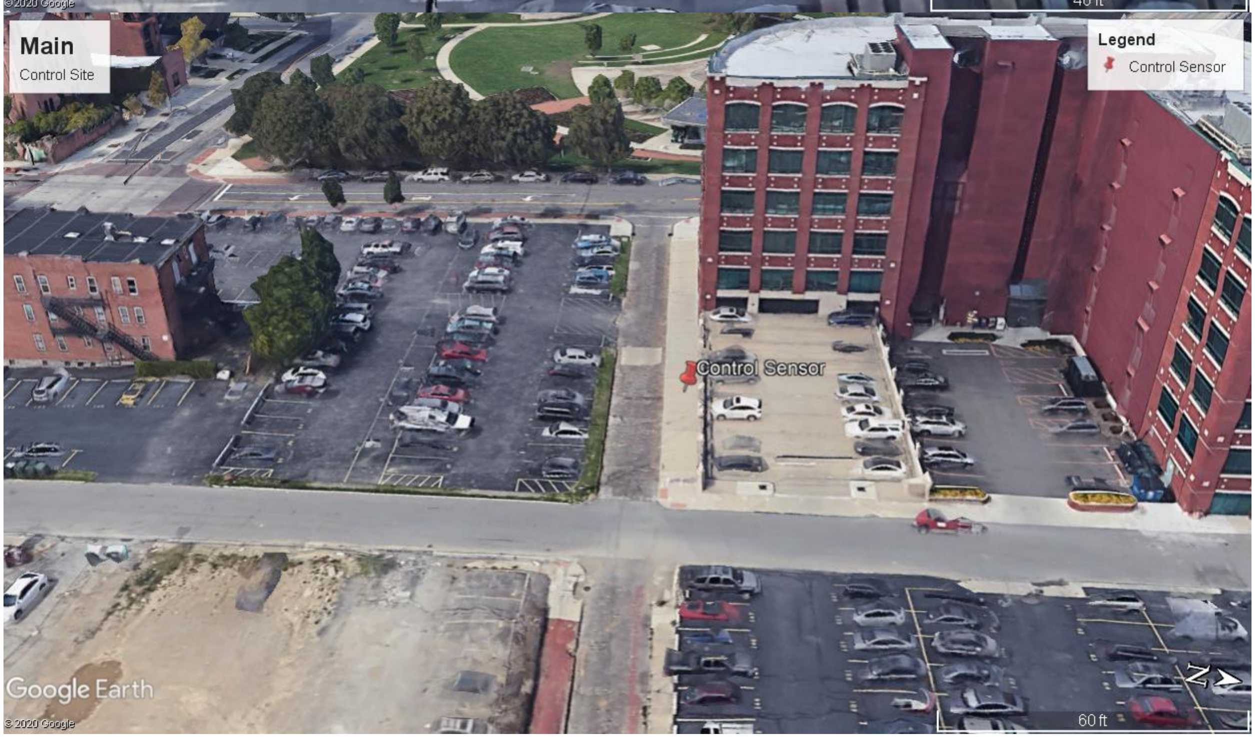

Main
Control Site
Legend
Control Sensor
Control Sensor
Google Earth
© 2020 Google
60 ft
N

Figure 35. Main treatment (top) and control (middle) sites satellite imagery, treatment sensors (bottom left), and control sensors (bottom right).

Figure 36. Star treatment and control sites satellite imagery (top) before bioretention installation, treatment sensors (bottom left), and control sensors (bottom right).

Figure 37. Whetstone treatment and control sites satellite imagery (top), treatment sensors (bottom left), and control sensors (bottom right).

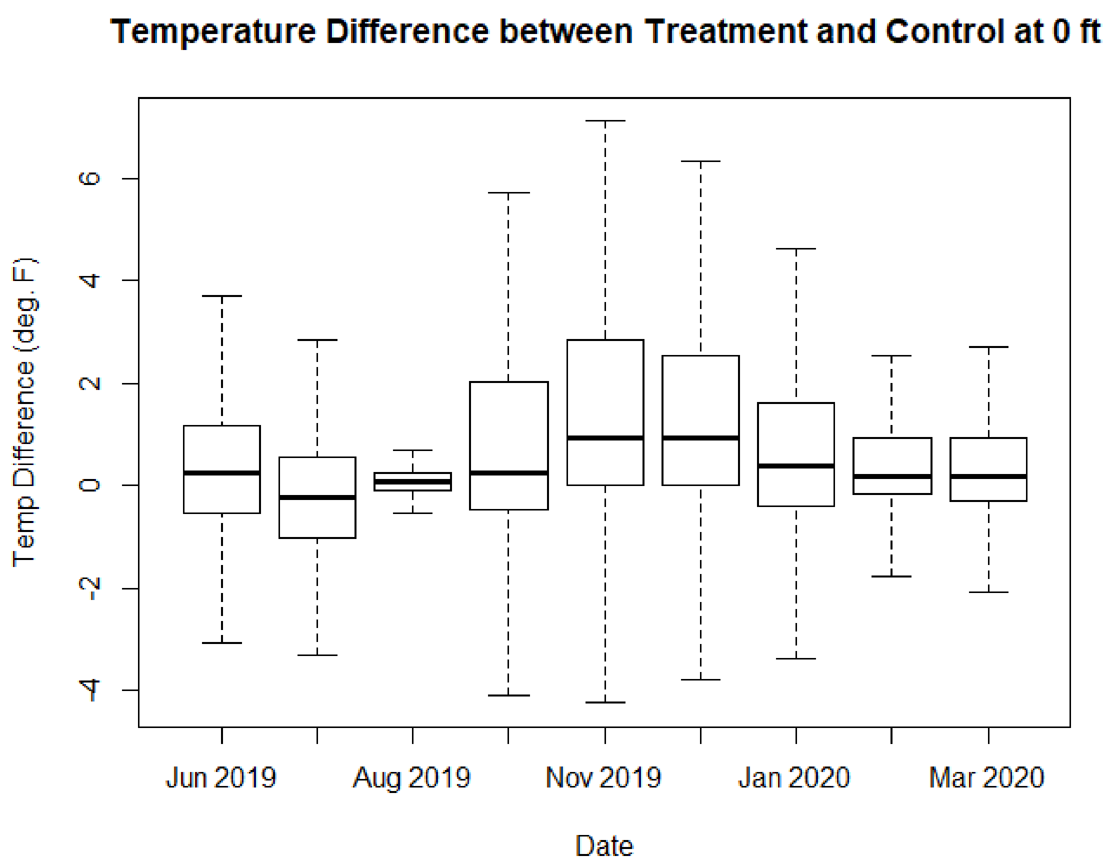
Appendix B. Figures of Temperature Differences for Each Site

Audubon

Table 18. Audubon Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-7.03	-0.54	0.23	0.22	1.16	5.64
2019 07	-14.36	-1.01	-0.23	-0.51	0.54	7.49
2019 08	-2.86	-0.08	0.08	0.06	0.23	1.63
2019 09	Sensor Malfunction					
2019 10	-9.66	-0.46	0.23	0.87	2.01	11.73
2019 11	-10.65	0.00	0.93	1.26	2.86	13.59
2019 12	-6.56	0.00	0.92	1.69	2.54	17.91
2020 01	-7.19	-0.39	0.38	0.78	1.62	11.82
2020 02	-6.57	-0.15	0.16	0.53	0.93	7.42
2020 03	-6.95	-0.30	0.16	0.30	0.92	6.33

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



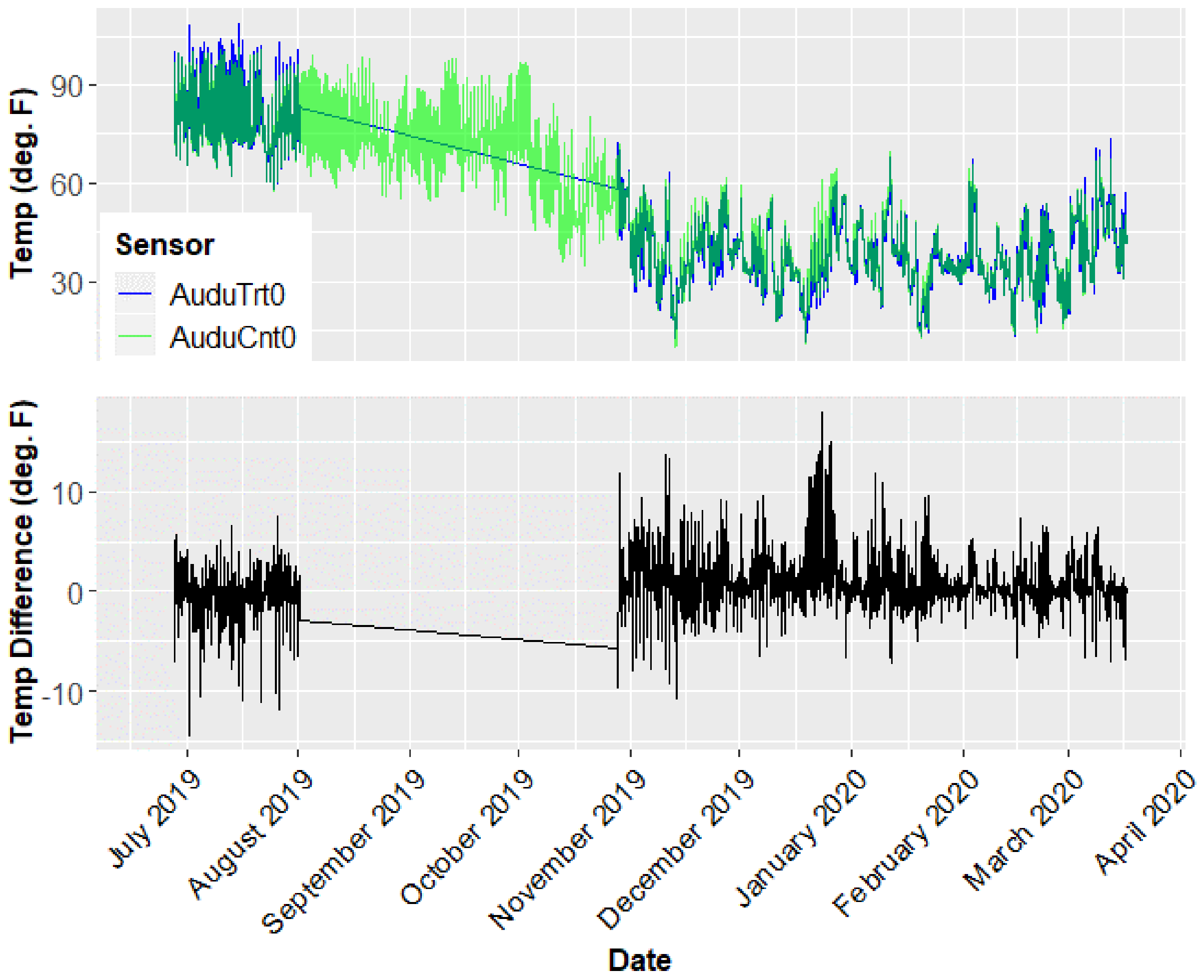
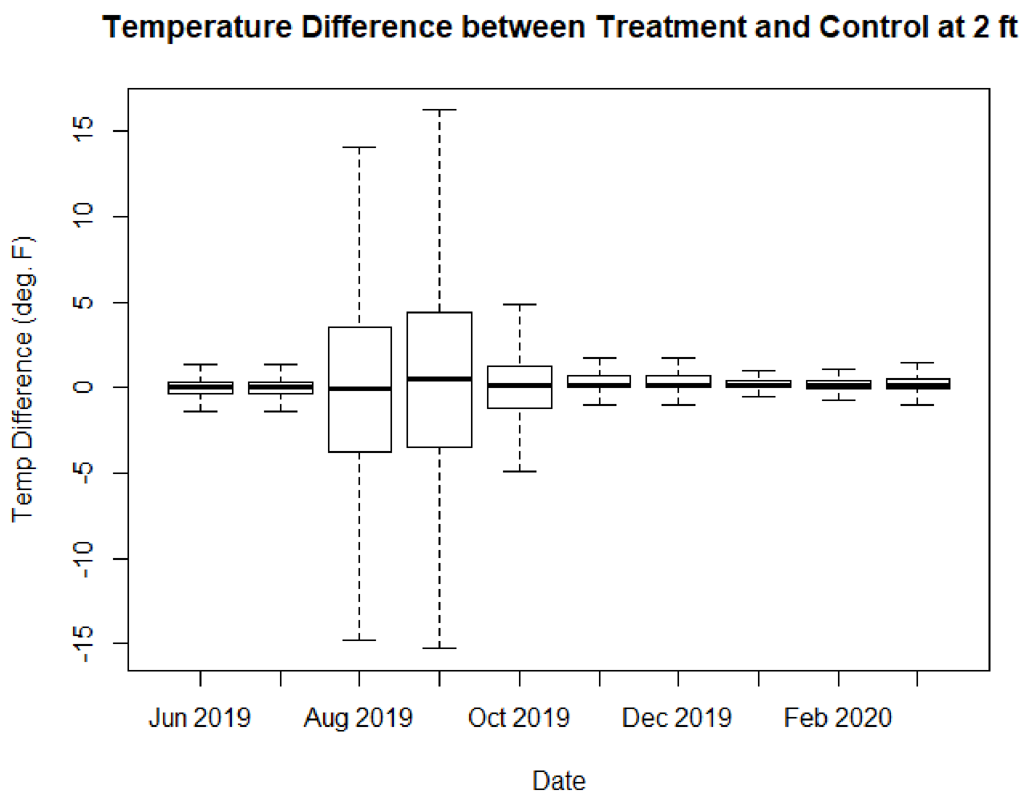


Table 19. Audubon Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-4.87	-0.38	0.00	-0.10	0.31	1.93
2019 07	-5.71	-0.39	0.00	-0.15	0.31	3.25
2019 08	-18.77	-3.78	-0.08	-0.35	3.55	14.06
2019 09	-22.70	-3.48	0.46	0.27	4.40	22.00
2019 10	-31.12	-1.23	0.15	-0.49	1.23	21.78
2019 11	-3.40	0.00	0.16	0.35	0.69	4.09
2019 12	-2.08	0.00	0.16	0.46	0.70	5.79
2020 01	-2.32	0.00	0.08	0.26	0.38	3.93
2020 02	-3.86	-0.08	0.08	0.16	0.39	3.55
2020 03	-4.24	-0.08	0.08	0.13	0.54	3.32

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Temperature Difference between Treatment and Control at 2 ft
Temp Difference (deg. F)
15
10
5
0
-5
-10
-15
Jun 2019
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date

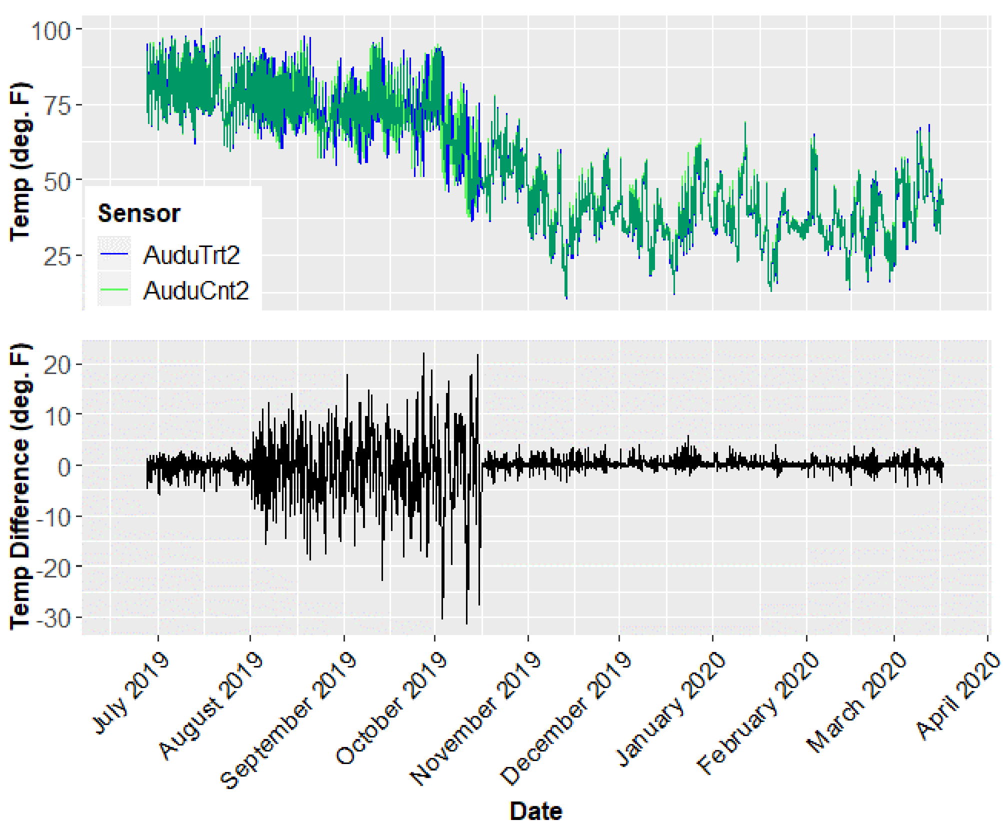
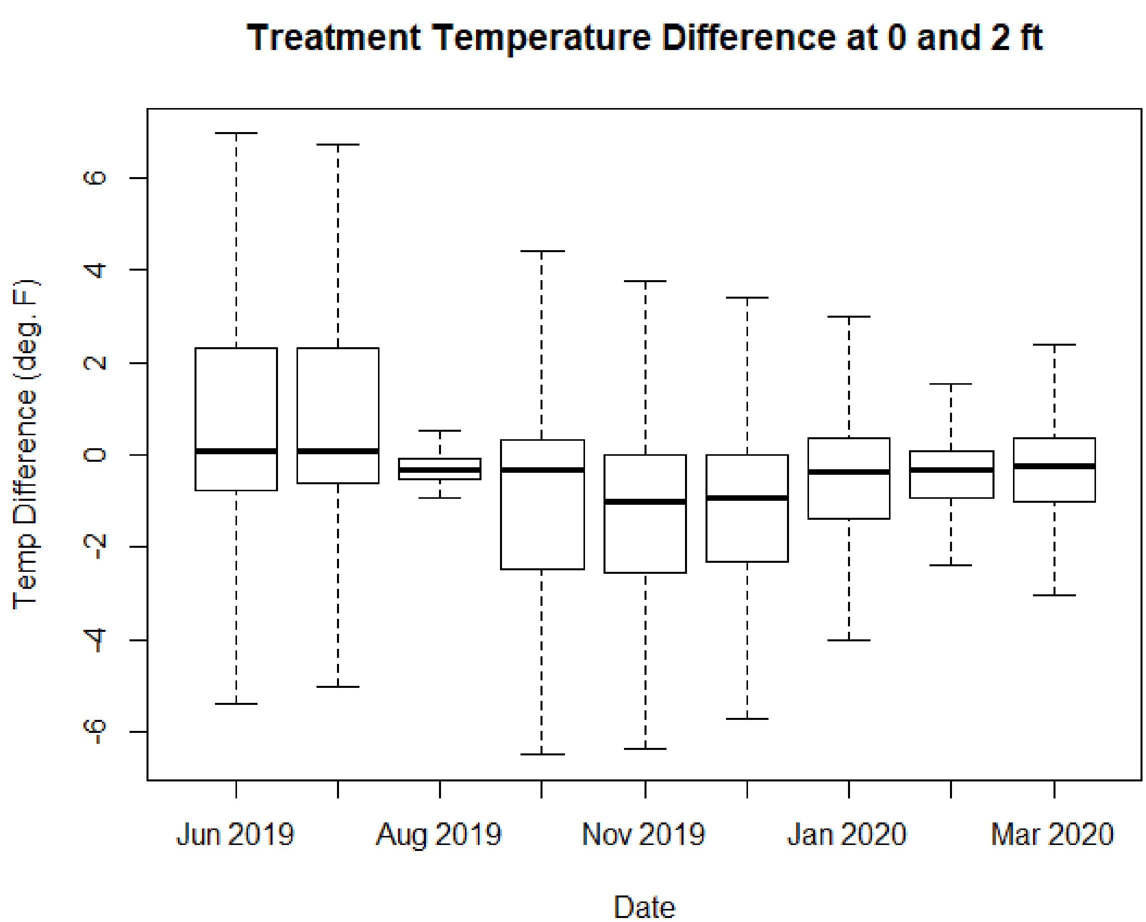

Temp (deg. F)
100
75
50
25
Sensor
AuduTrt2
AuduCnt2
Temp Difference (deg. F)
20
10
0
-10
-20
-30
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Table 20. Audubon Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-5.64	-0.77	0.07	0.69	2.32	7.03
2019 07	-7.26	-0.62	0.08	1.00	2.32	16.14
2019 08	-0.93	-0.54	-0.31	-0.08	-0.08	5.02
2019 09	Sensor Malfunction					
2019 10	-10.73	-2.47	-0.31	-0.87	0.31	9.11
2019 11	-13.05	-2.55	-1.00	-1.04	0.00	9.89
2019 12	-13.67	-2.31	-0.92	-1.39	0.00	7.03
2020 01	-9.19	-1.39	-0.38	-0.59	0.38	7.11
2020 02	-7.49	-0.93	-0.31	-0.44	0.08	6.49
2020 03	-7.57	-1.00	-0.24	-0.12	0.38	7.80

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



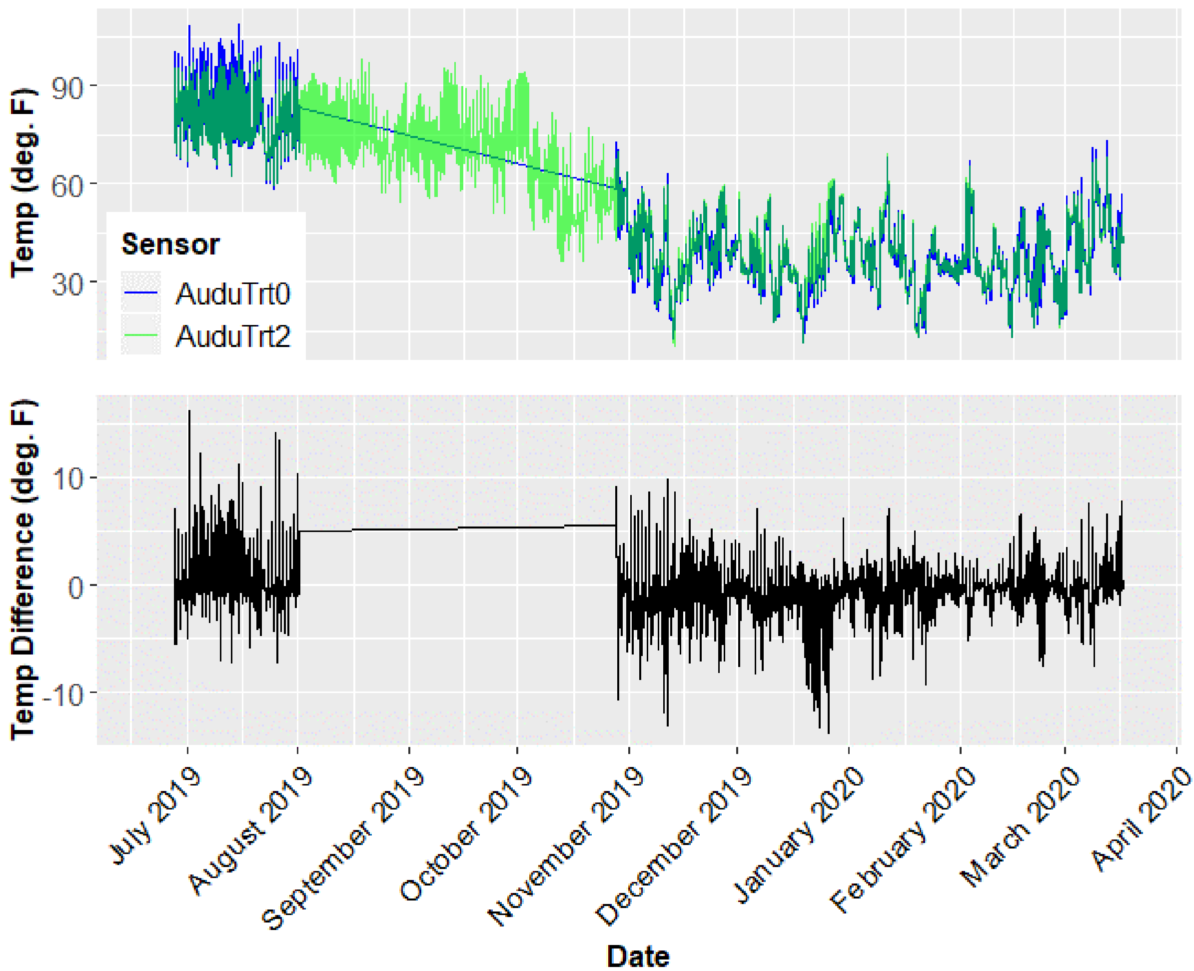
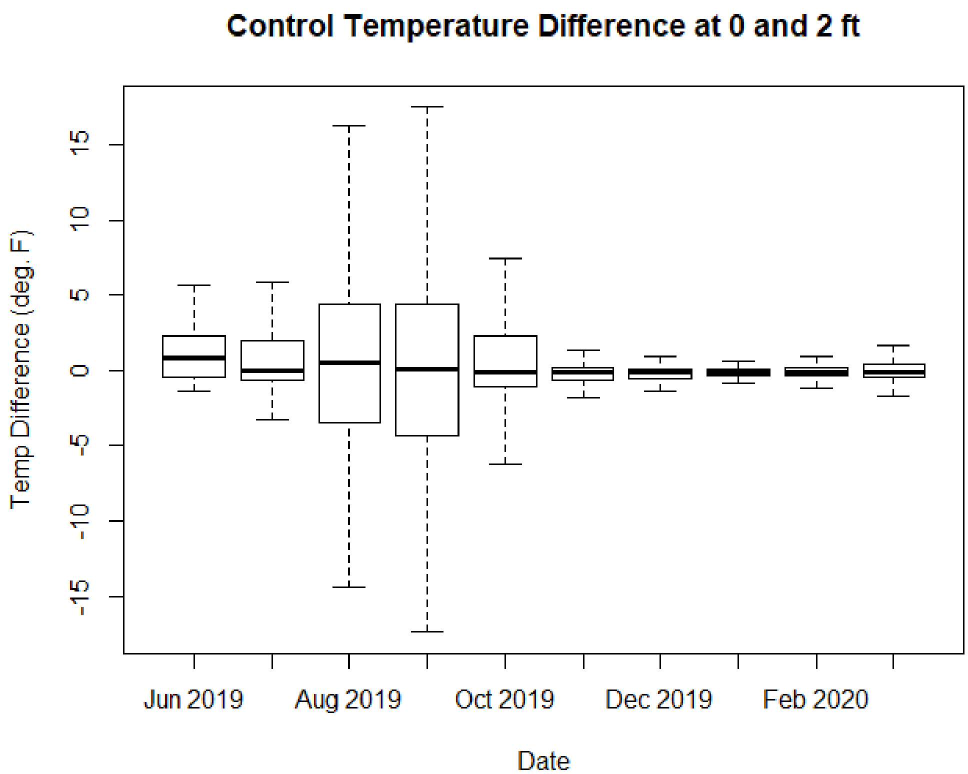
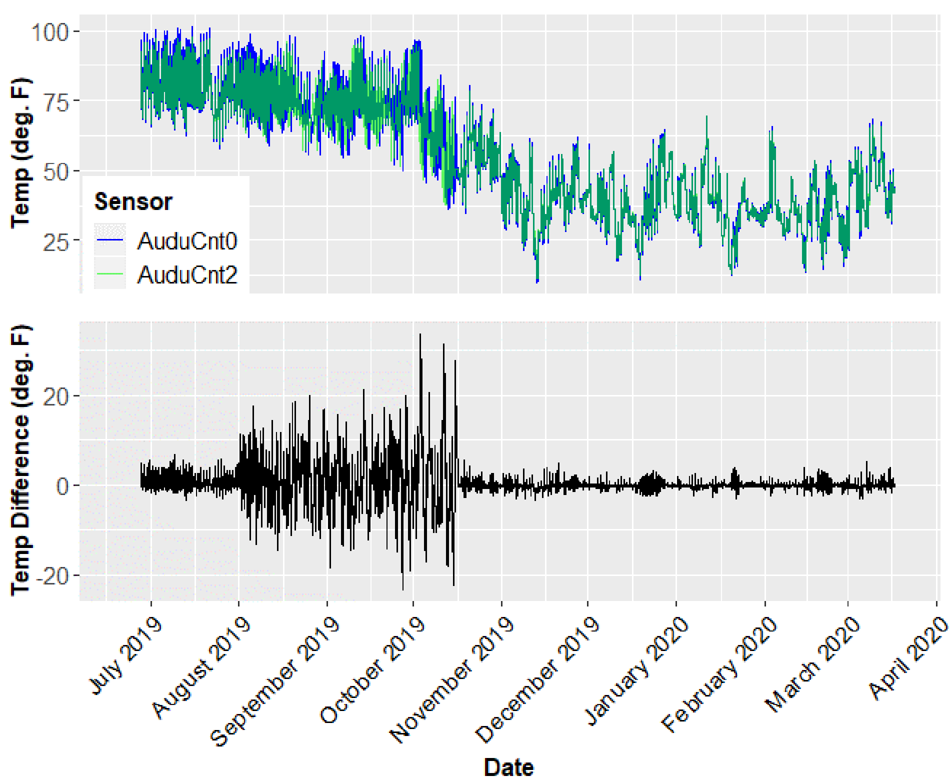


Table 21. Audubon Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-1.39	-0.46	0.77	1.01	2.24	5.64
2019 07	-3.32	-0.62	0.00	0.64	2.00	6.95
2019 08	-14.36	-3.48	0.54	0.68	4.41	19.92
2019 09	-23.24	-4.32	0.07	0.09	4.40	21.32
2019 10	-22.24	-1.08	-0.16	0.75	2.32	33.66
2019 11	-3.25	-0.62	-0.16	-0.13	0.16	4.71
2019 12	-2.47	-0.54	-0.16	-0.16	0.07	3.09
2020 01	-3.17	-0.31	-0.15	-0.07	0.07	3.79
2020 02	-2.47	-0.39	-0.15	-0.07	0.15	3.86
2020 03	-3.17	-0.46	-0.15	0.05	0.38	5.33

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
15
10
5
0
-5
-10
-15
Jun 2019
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date

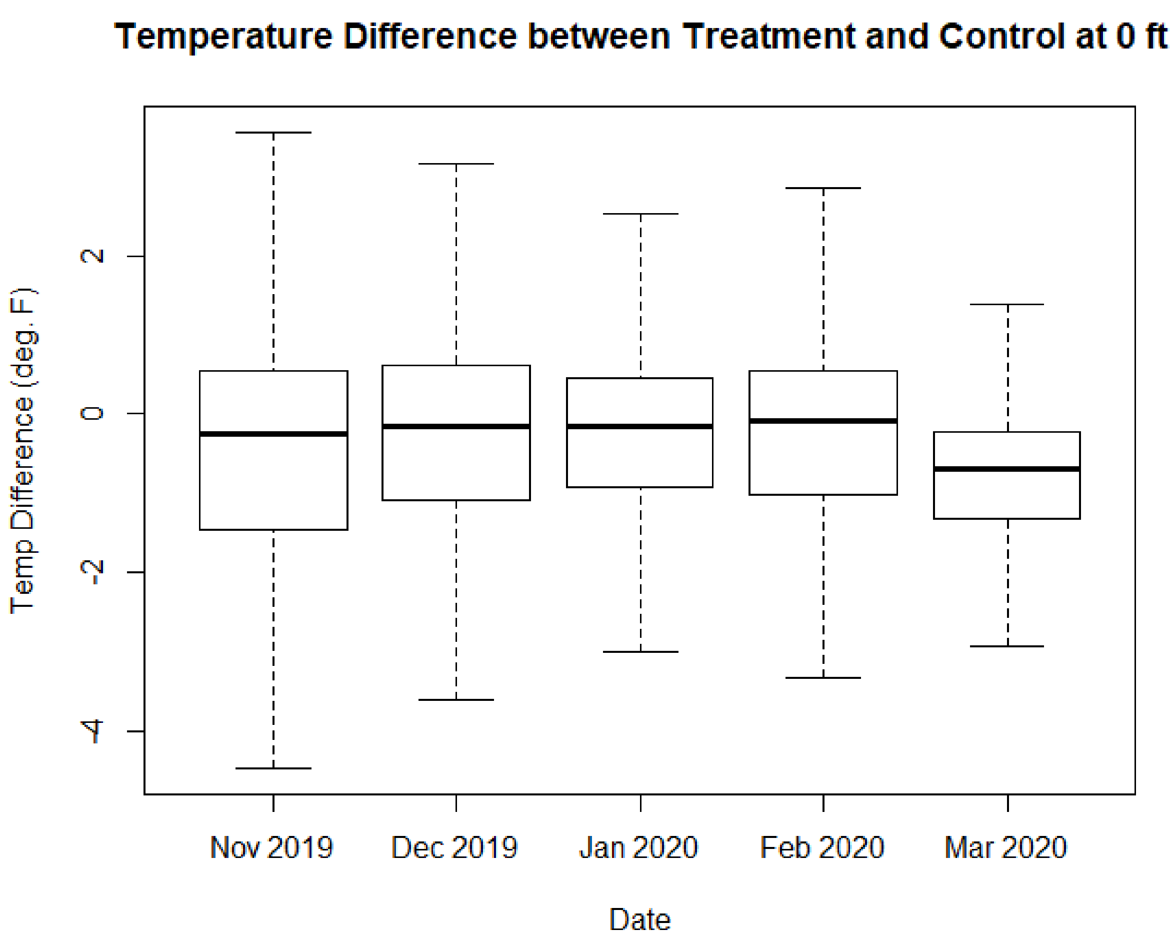

Temp (deg. F)
100
75
50
25
Sensor
AuduCnt0
AuduCnt2
Temp Difference (deg. F)
20
0
-20
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Blenheim

Table 22. Blenheim Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 7	Sensor Malfunction					
2019 8						
2019 9						
2019 10						
2019 11	-12.36	-1.46	-0.24	-0.29	0.55	10.58
2019 12	-10.51	-1.08	-0.16	-0.38	0.62	13.82
2020 01	-8.49	-0.93	-0.15	-0.28	0.46	7.88
2020 02	-12.12	-1.01	-0.08	-0.32	0.54	9.96
2020 03	-9.58	-1.31	-0.70	-0.98	-0.23	3.02

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



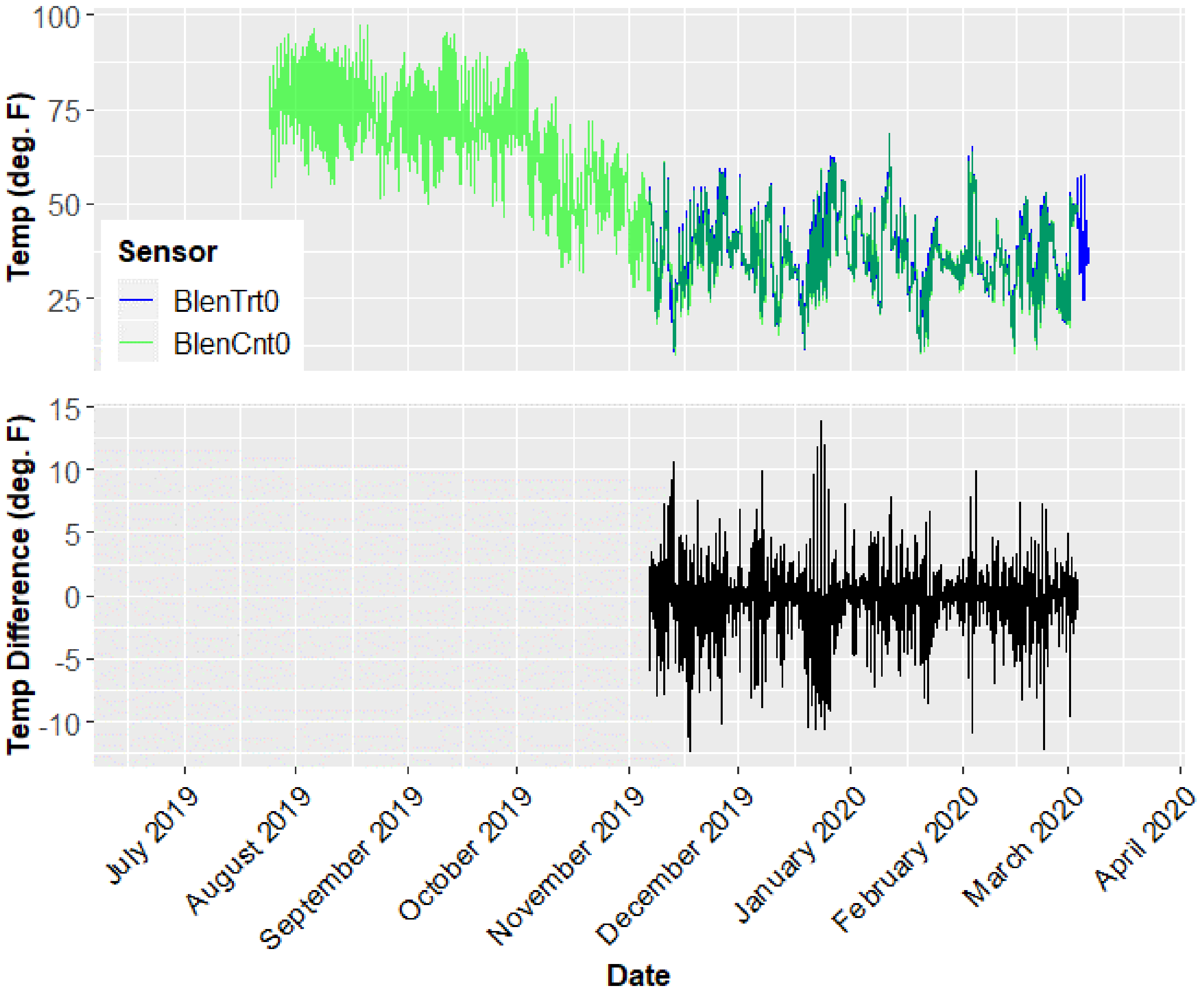
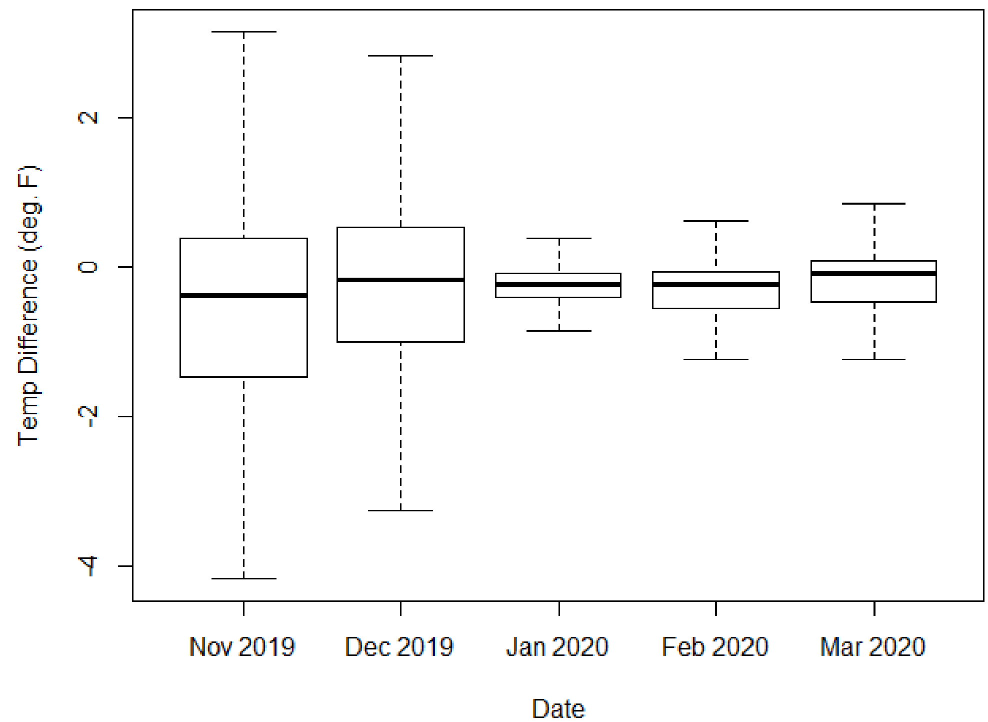


Table 23. Blenheim Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 7	Sensor Malfunction					
2019 8						
2019 9						
2019 10						
2019 11	-11.66	-1.46	-0.38	-0.58	0.39	7.95
2019 12	-8.57	-1.00	-0.16	-0.32	0.54	7.80
2020 01	-3.70	-0.39	-0.23	-0.32	-0.08	1.85
2020 02	-3.79	-0.54	-0.23	-0.33	-0.07	3.71
2020 03	-2.39	-0.46	-0.08	-0.19	0.08	2.40

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



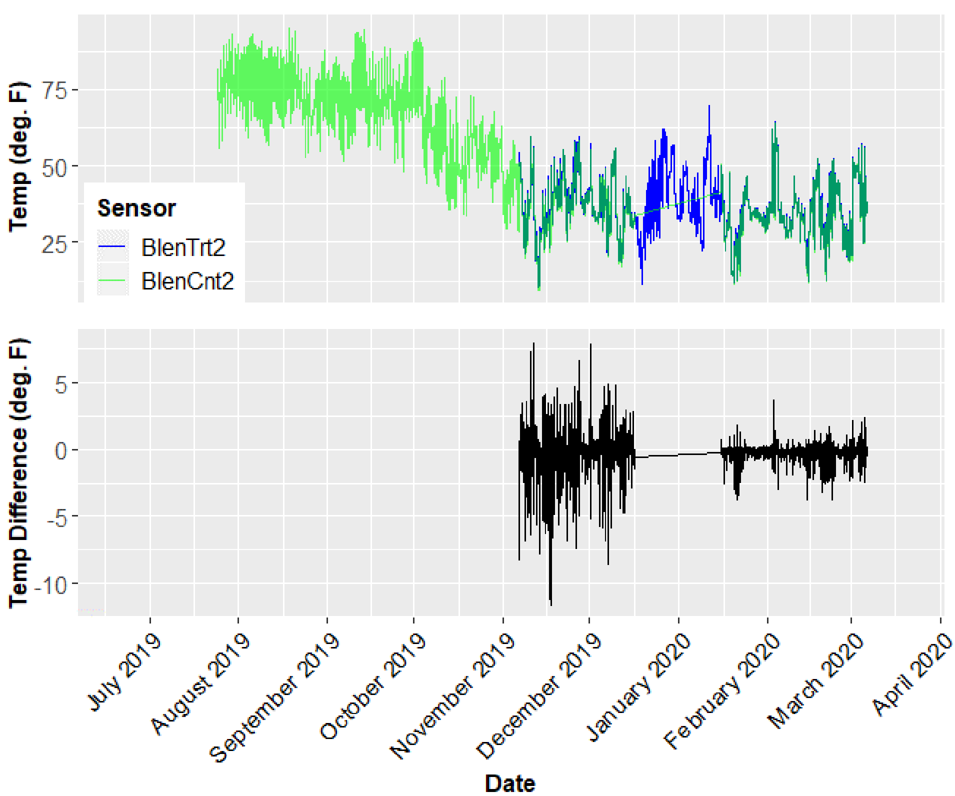
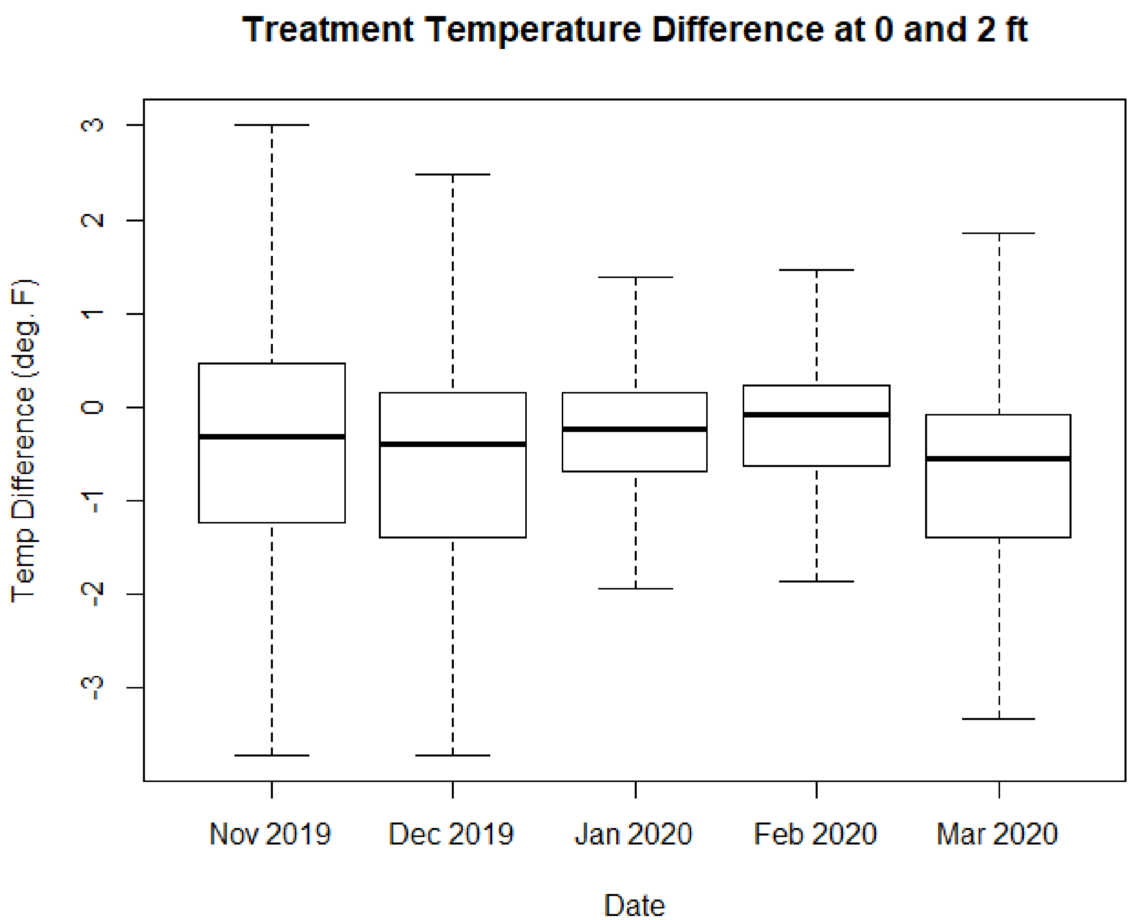


Table 24. Blenheim Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 7	Sensor Malfunction					
2019 8						
2019 9						
2019 10						
2019 11	-4.63	-1.23	-0.31	-0.34	0.47	4.33
2019 12	-5.33	-1.39	-0.39	-0.60	0.16	3.78
2020 01	-2.55	-0.69	-0.23	-0.25	0.15	3.24
2020 02	-5.49	-0.62	-0.08	-0.27	0.23	3.56
2020 03	-3.32	-1.39	-0.54	-0.63	-0.08	2.32

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



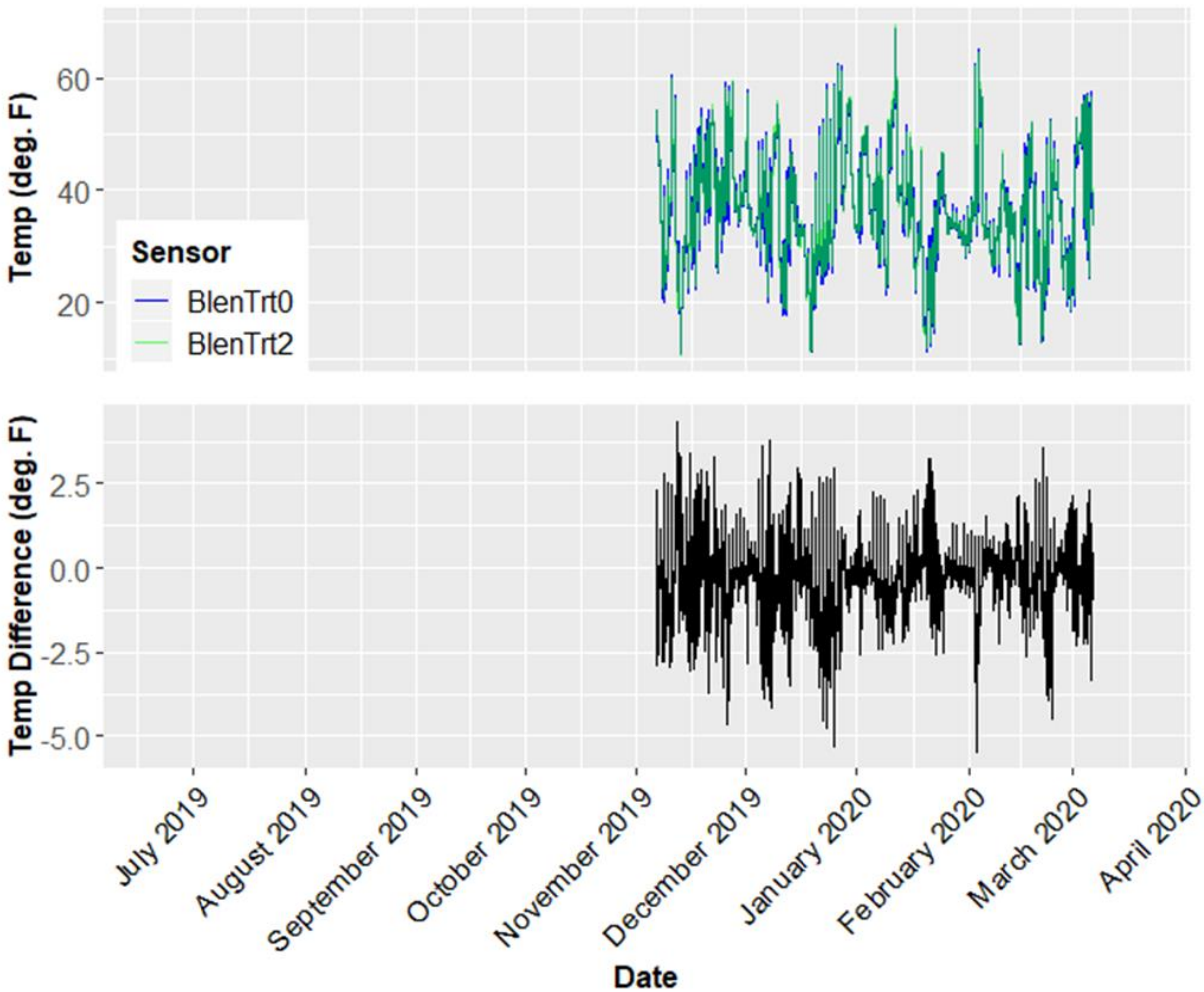
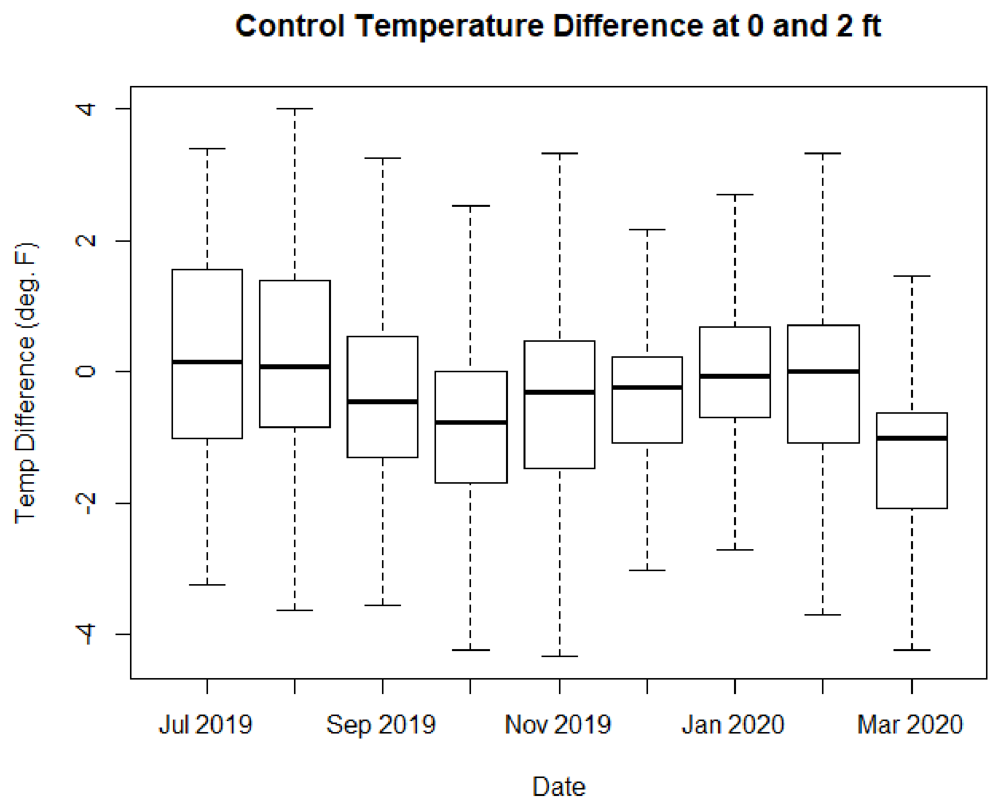
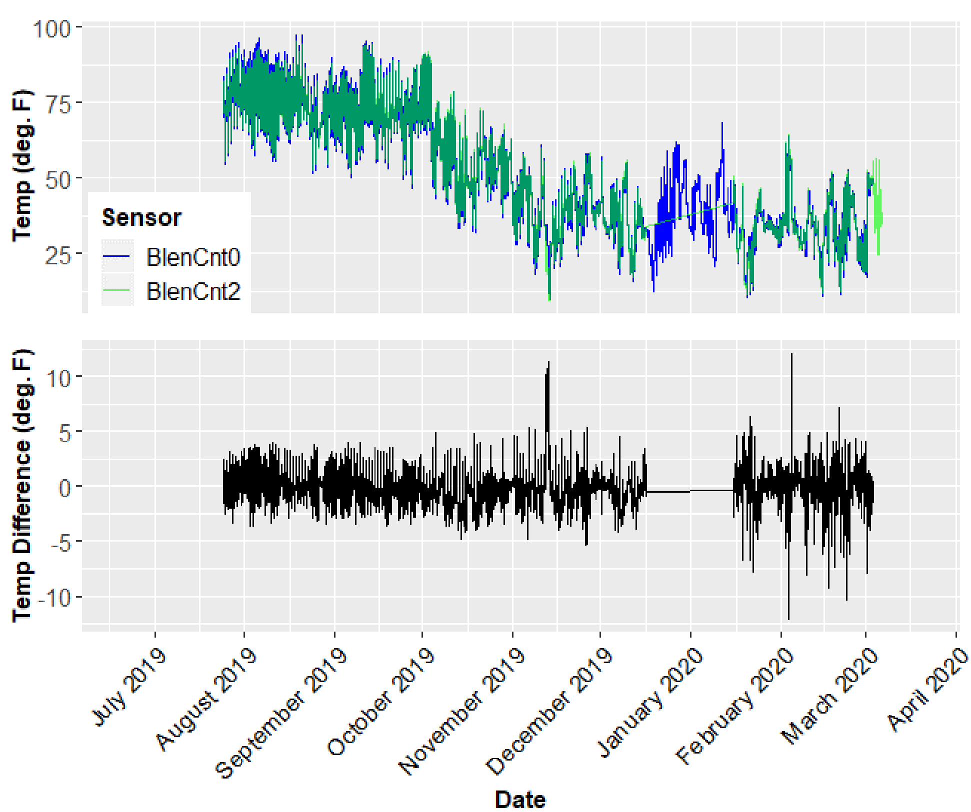


Table 25. Blenheim Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-3.25	-1.01	0.16	0.29	1.55	3.40
2019 08	-3.63	-0.85	0.07	0.22	1.39	4.01
2019 09	-3.56	-1.31	-0.46	-0.26	0.54	3.94
2019 10	-4.86	-1.70	-0.77	-0.79	0.00	4.95
2019 11	-5.33	-1.47	-0.31	-0.16	0.46	11.43
2019 12	-4.17	-1.08	-0.23	-0.45	0.23	4.48
2020 01	-7.80	-0.69	-0.07	-0.06	0.69	6.33
2020 02	-12.12	-1.08	0.00	-0.27	0.70	12.05
2020 03	-7.96	-2.09	-1.00	-1.40	-0.62	1.47

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
4
2
0
-2
-4
Jul 2019
Sep 2019
Nov 2019
Jan 2020
Mar 2020
Date

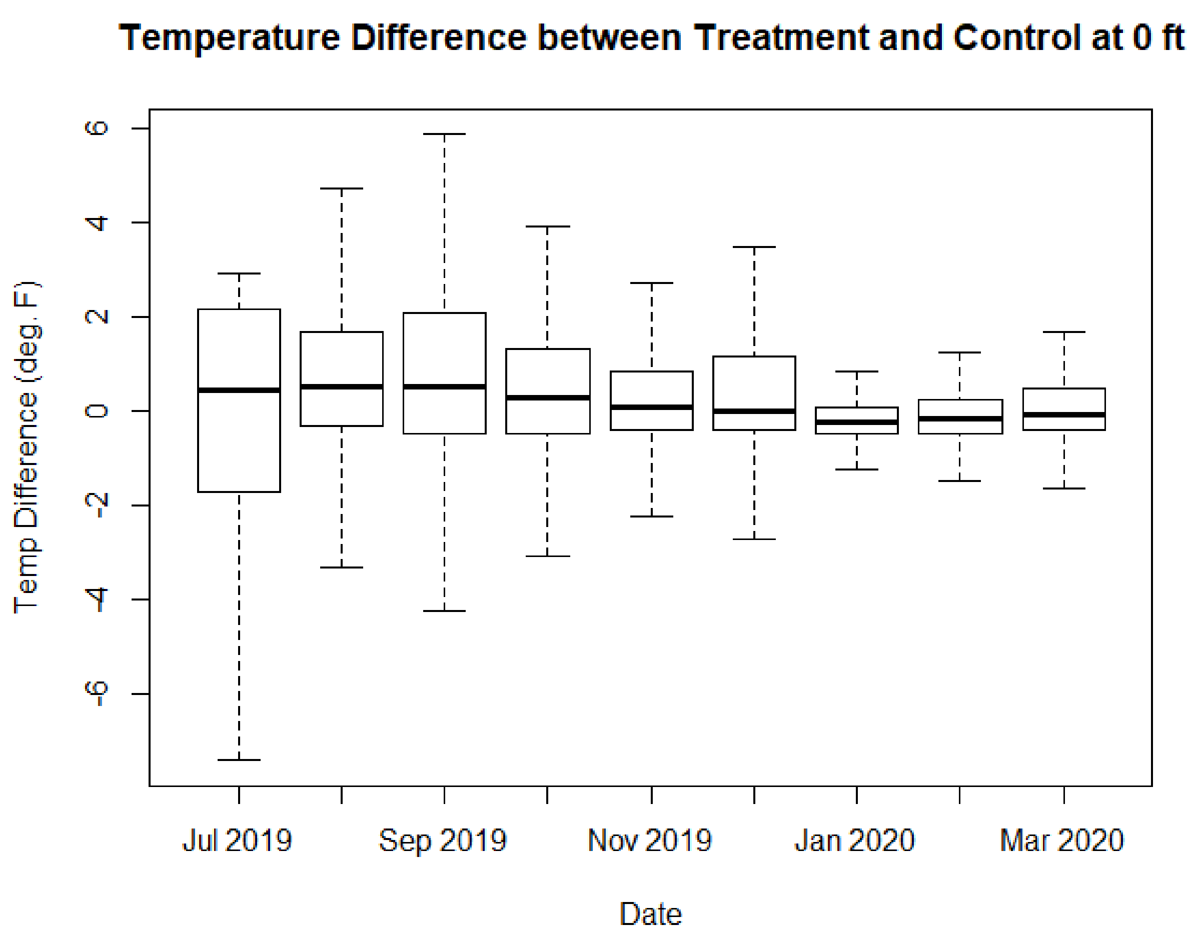

Temp (deg. F)
100
75
50
25
Sensor
BlenCnt0
BlenCnt2
Temp Difference (deg. F)
10
5
0
-5
-10
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Canyon

Table 26. Canyon Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-9.73	-1.69	0.46	-0.59	2.16	2.94
2019 08	-15.75	-0.31	0.54	0.41	1.70	11.89
2019 09	-12.20	-0.46	0.54	0.64	2.09	12.59
2019 10	-10.97	-0.46	0.30	0.40	1.31	12.82
2019 11	-5.72	-0.39	0.08	0.33	0.85	9.50
2019 12	-7.03	-0.39	0.00	0.38	1.16	6.10
2020 01	-5.79	-0.46	-0.23	-0.15	0.08	3.71
2020 02	-4.40	-0.46	-0.16	-0.03	0.23	5.72
2020 03	-5.41	-0.39	-0.08	0.03	0.47	7.26

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



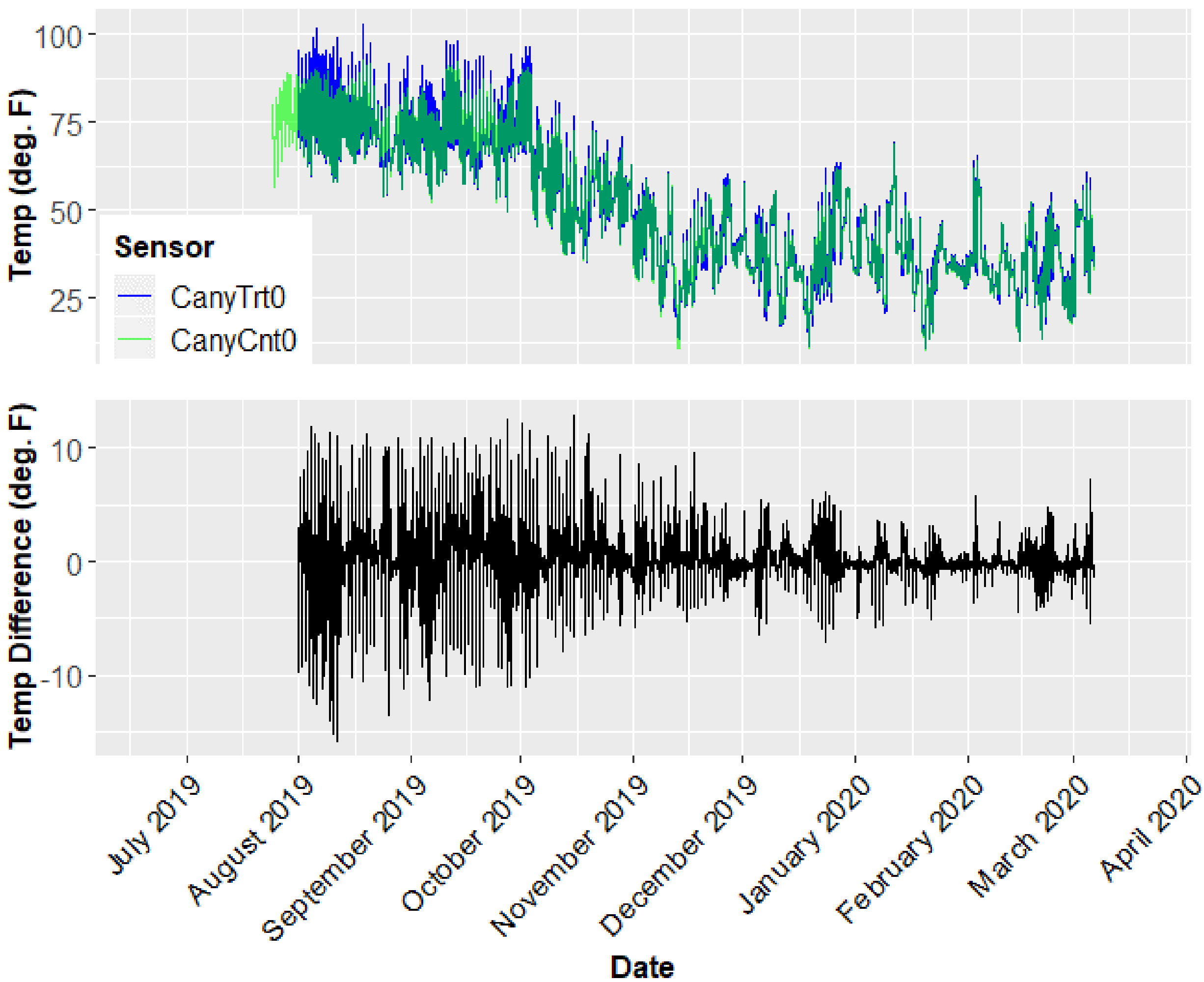
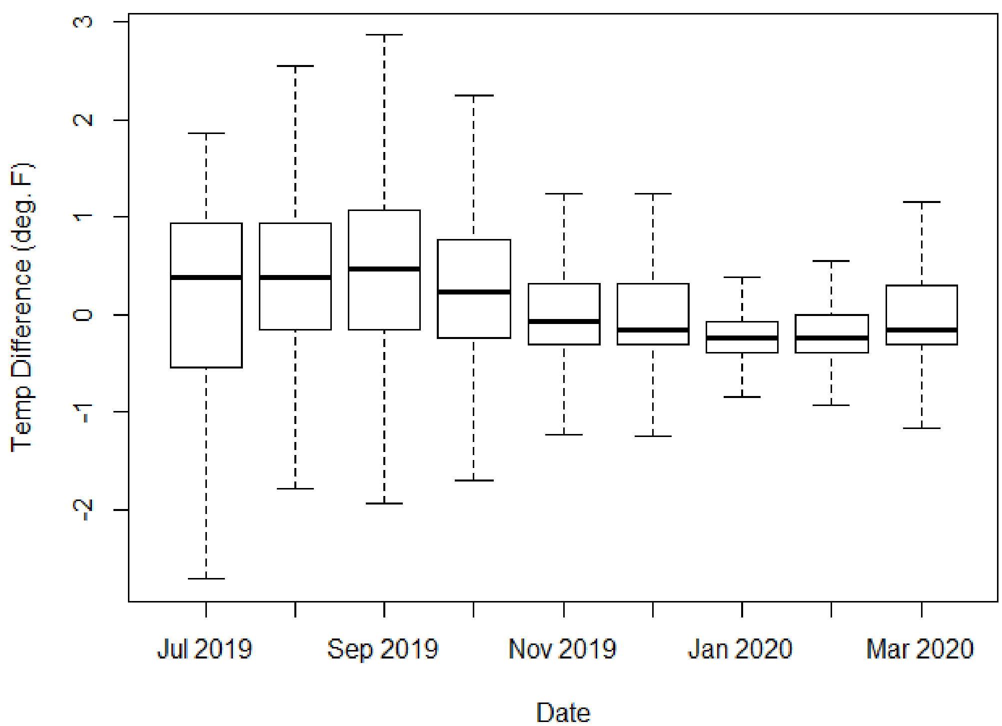


Table 27. Canyon Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-5.10	-0.54	0.39	-0.14	0.93	1.86
2019 08	-6.33	-0.16	0.39	0.31	0.93	5.41
2019 09	-5.02	-0.15	0.46	0.41	1.08	6.41
2019 10	-5.10	-0.23	0.23	0.21	0.77	7.42
2019 11	-4.02	-0.31	-0.07	-0.04	0.31	4.86
2019 12	-3.94	-0.31	-0.15	0.01	0.31	4.17
2020 01	-3.40	-0.38	-0.23	-0.21	-0.07	2.24
2020 02	-4.10	-0.39	-0.23	-0.18	0.00	4.10
2020 03	-2.24	-0.31	-0.15	0.04	0.30	6.02

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



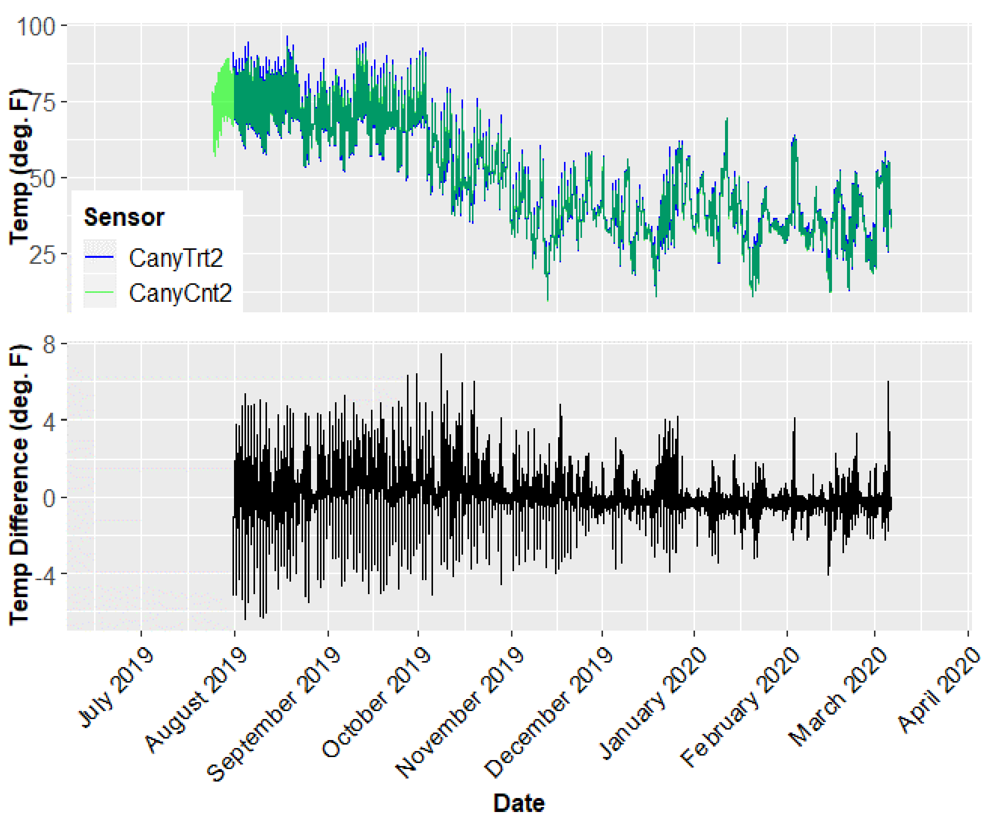
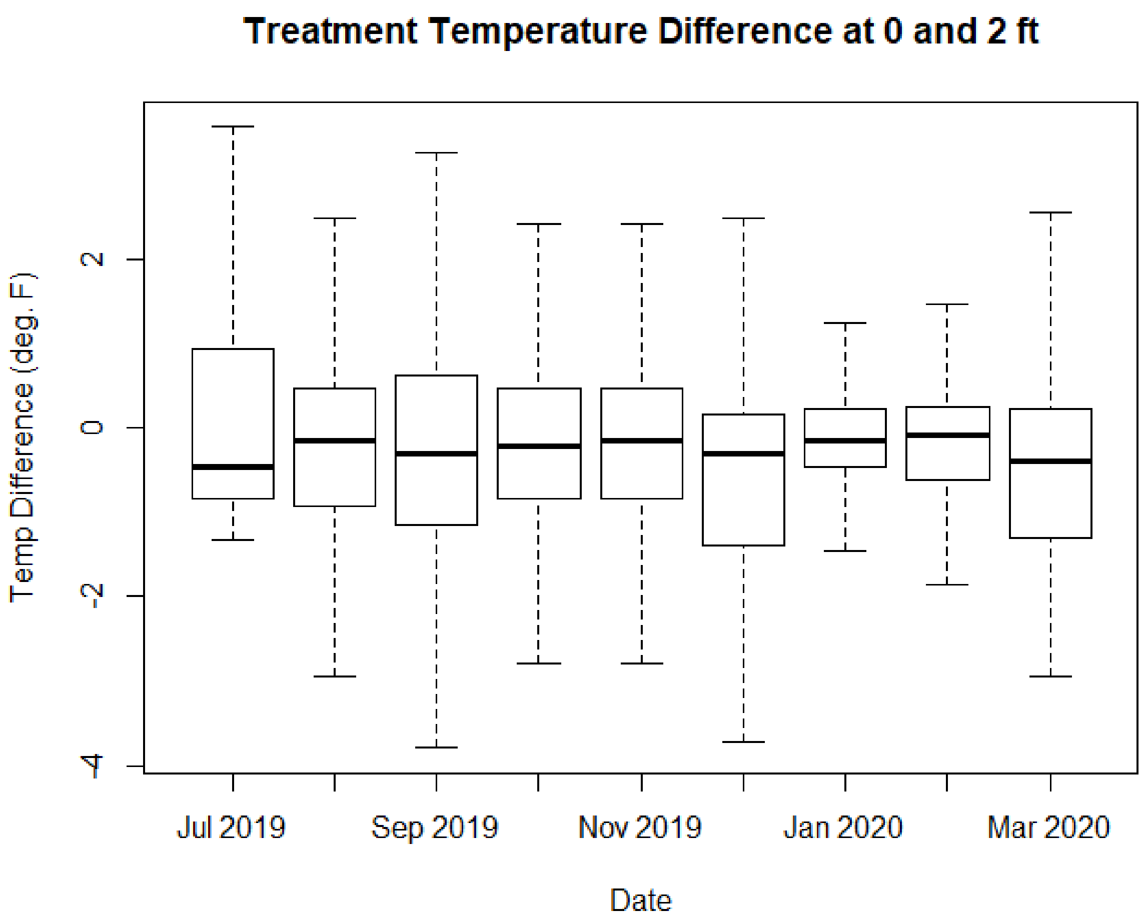


Table 28. Canyon Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-1.32	-0.85	-0.46	0.48	0.91	5.41
2019 08	-5.02	-0.92	-0.15	0.11	0.46	11.12
2019 09	-5.87	-1.16	-0.31	-0.20	0.61	8.19
2019 10	-5.18	-0.85	-0.23	-0.19	0.47	6.56
2019 11	-4.71	-0.84	-0.15	-0.19	0.46	5.10
2019 12	-5.33	-1.39	-0.31	-0.66	0.16	3.71
2020 01	-3.40	-0.47	-0.15	-0.16	0.23	3.48
2020 02	-5.25	-0.62	-0.08	-0.28	0.24	3.86
2020 03	-2.94	-1.31	-0.39	-0.30	0.23	5.95

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



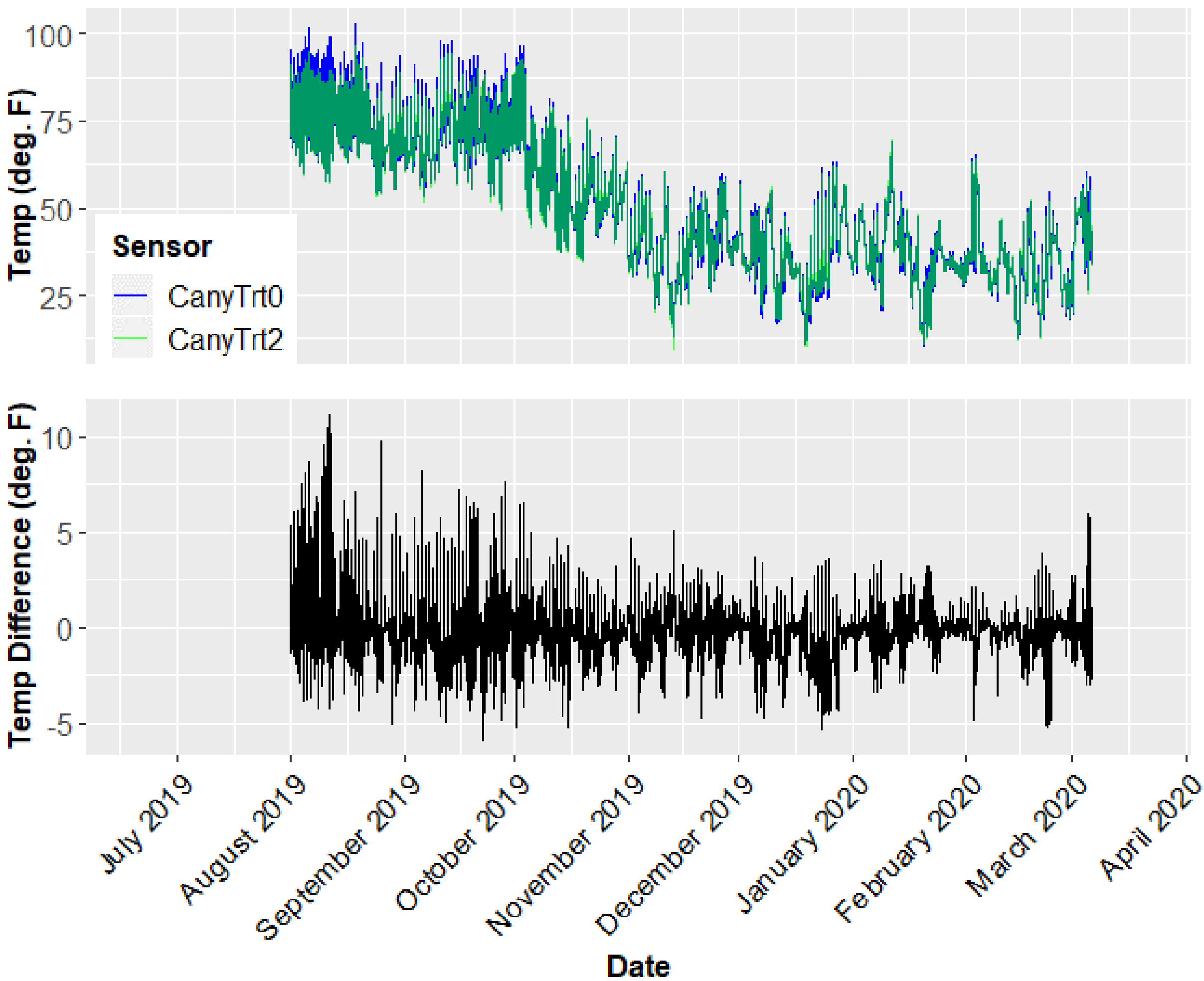
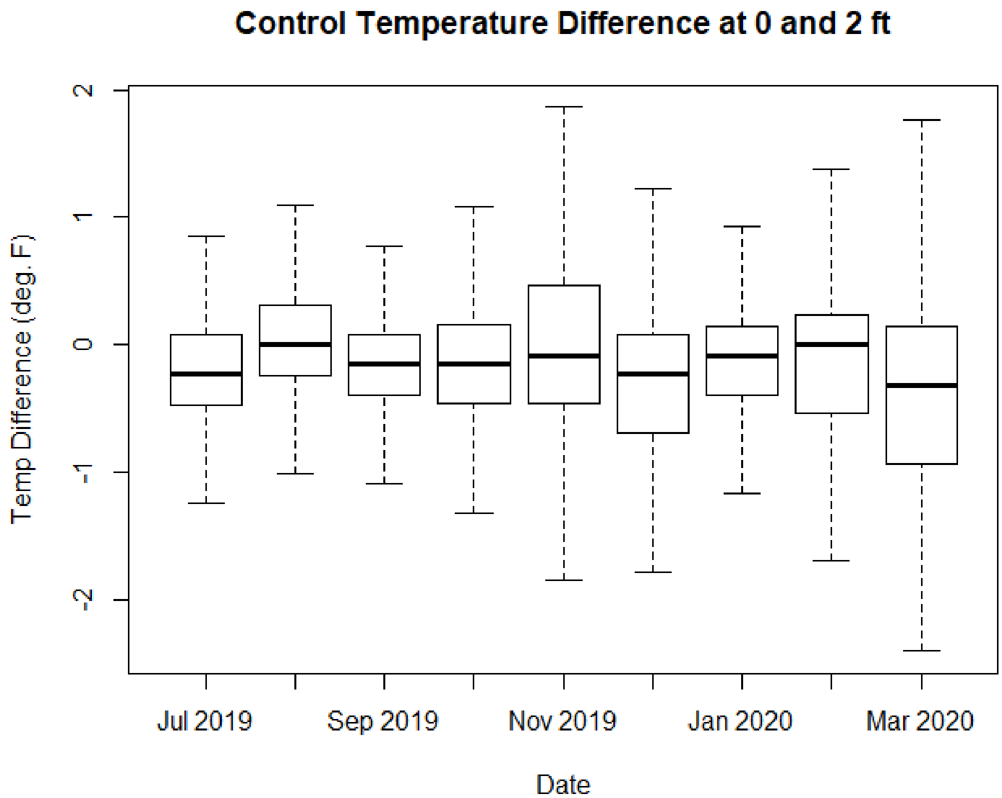
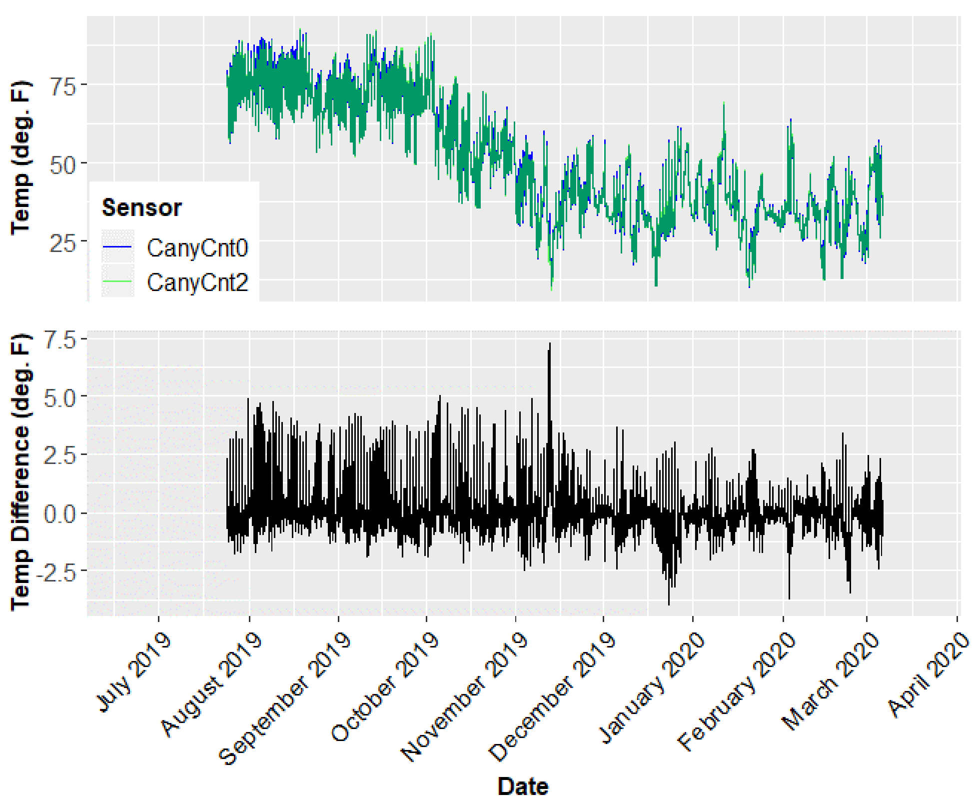


Table 29. Canyon Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-1.78	-0.47	-0.23	-0.01	0.08	4.86
2019 08	-1.70	-0.24	0.00	0.21	0.31	4.78
2019 09	-1.93	-0.39	-0.15	0.03	0.08	4.25
2019 10	-2.16	-0.46	-0.15	0.00	0.16	5.02
2019 11	-2.47	-0.46	-0.08	0.17	0.47	7.26
2019 12	-3.94	-0.69	-0.23	-0.28	0.08	3.63
2020 01	-2.01	-0.39	-0.08	-0.10	0.15	2.78
2020 02	-3.71	-0.54	0.00	-0.12	0.23	3.40
2020 03	-2.40	-0.93	-0.31	-0.31	0.15	2.40

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
2
1
0
-1
-2
Jul 2019
Sep 2019
Nov 2019
Jan 2020
Mar 2020
Date

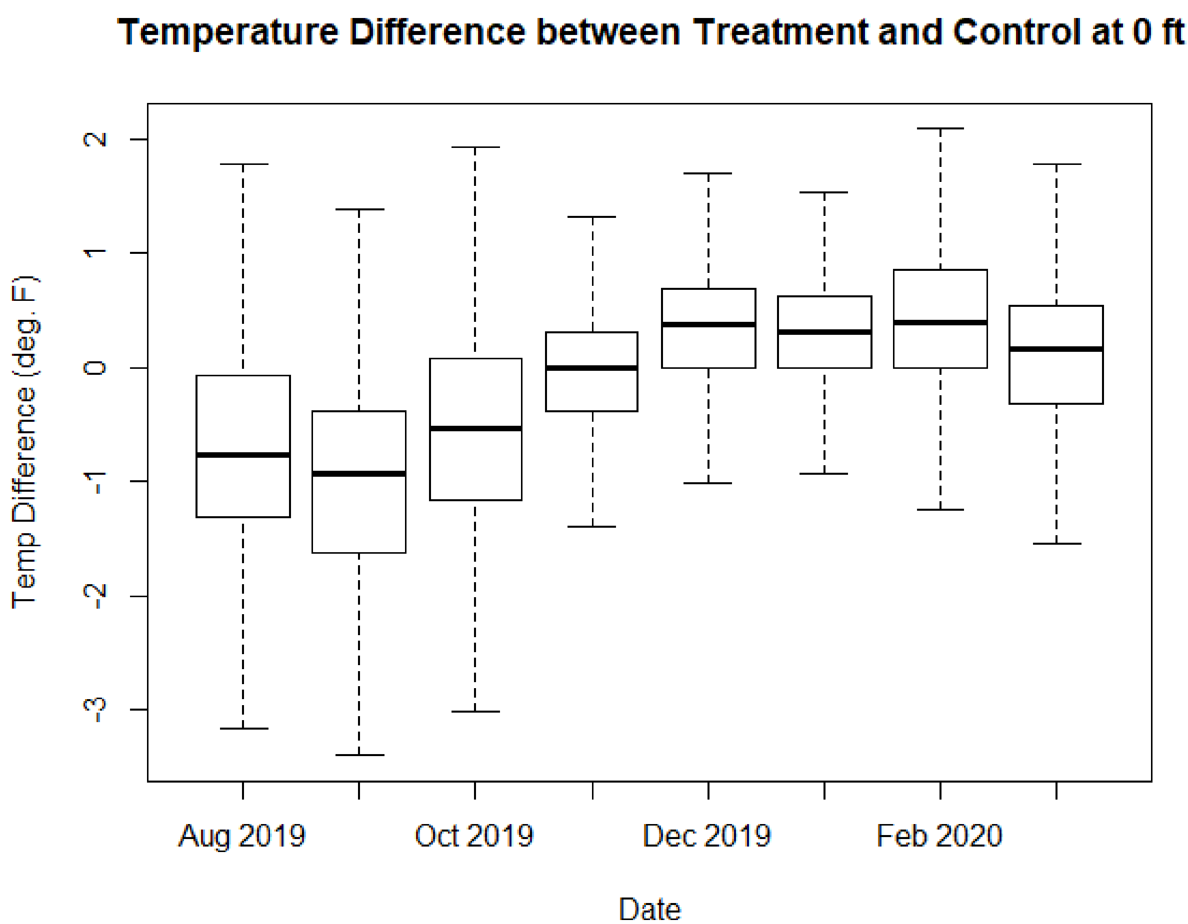

Temp (deg. F)
75
50
25
Sensor
CanyCnt0
CanyCnt2
Temp Difference (deg. F)
7.5
5.0
2.5
0.0
-2.5
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Front

Table 30. Front Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-9.19	-1.31	-0.77	-0.89	-0.07	18.53
2019 09	-8.49	-1.62	-0.93	-1.14	-0.39	3.56
2019 10	-7.64	-1.16	-0.54	-0.69	0.08	2.55
2019 11	-6.41	-0.39	0.00	-0.12	0.31	2.17
2019 12	-4.63	0.00	0.38	0.27	0.70	3.71
2020 01	-4.71	0.00	0.31	0.24	0.62	1.94
2020 02	-7.10	0.00	0.39	0.32	0.85	3.25
2020 03	-7.34	-0.31	0.16	-0.18	0.54	2.24

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



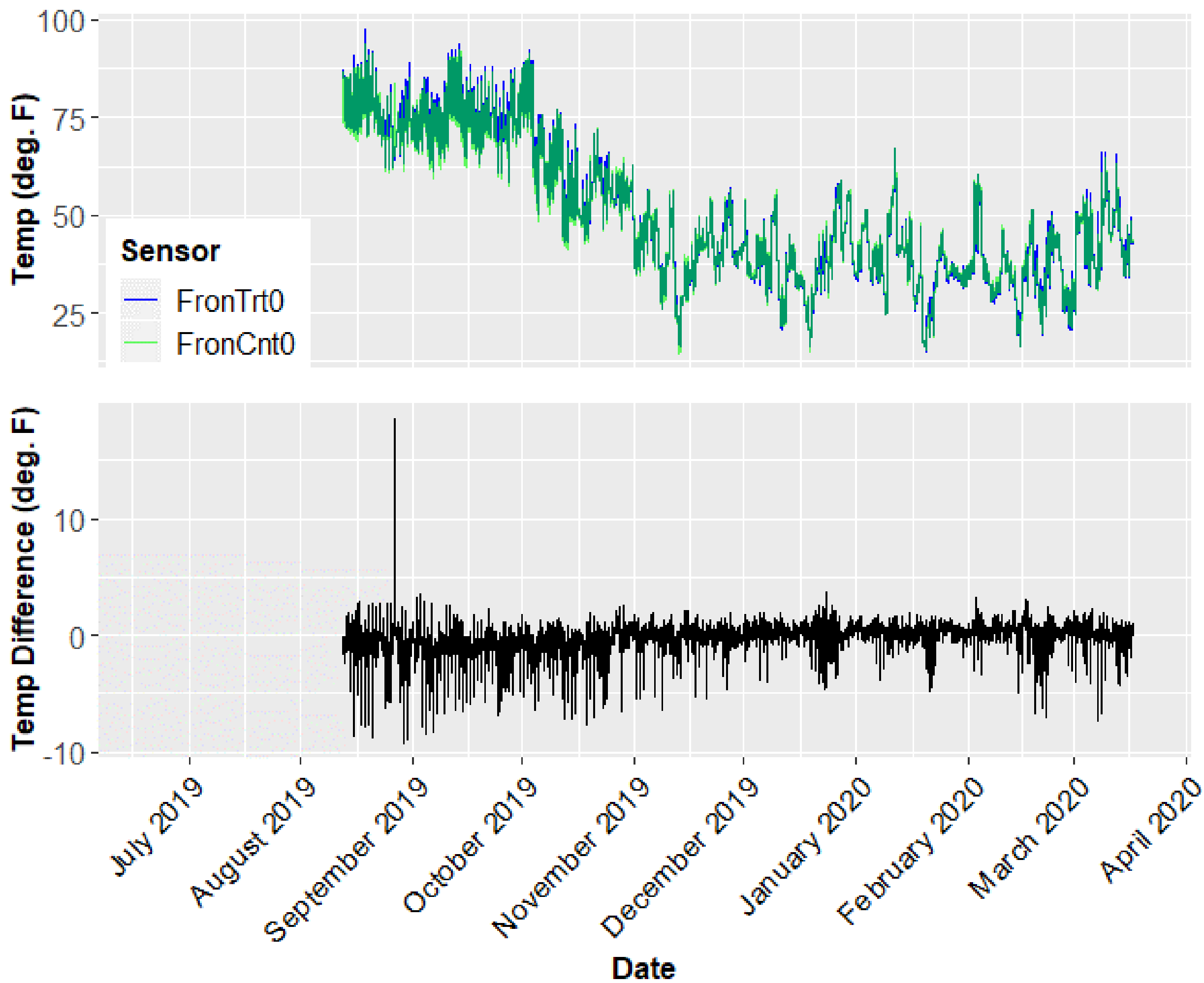
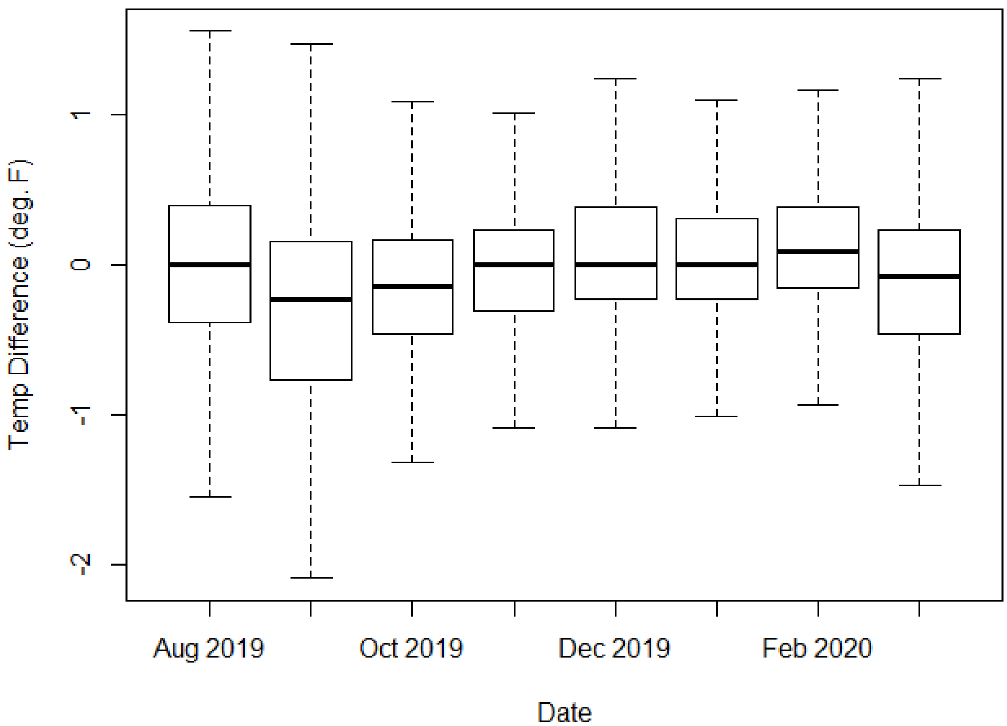


Table 31. Front Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-5.41	-0.39	0.00	-0.18	0.39	5.64
2019 09	-5.64	-0.77	-0.23	-0.42	0.15	4.02
2019 10	-4.10	-0.46	-0.15	-0.23	0.16	2.32
2019 11	-3.94	-0.31	0.00	-0.09	0.23	2.40
2019 12	-4.71	-0.23	0.00	-0.04	0.38	2.70
2020 01	-3.24	-0.23	0.00	0.02	0.31	4.17
2020 02	-4.02	-0.16	0.08	0.02	0.38	2.00
2020 03	-4.64	-0.46	-0.08	-0.27	0.23	1.70

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



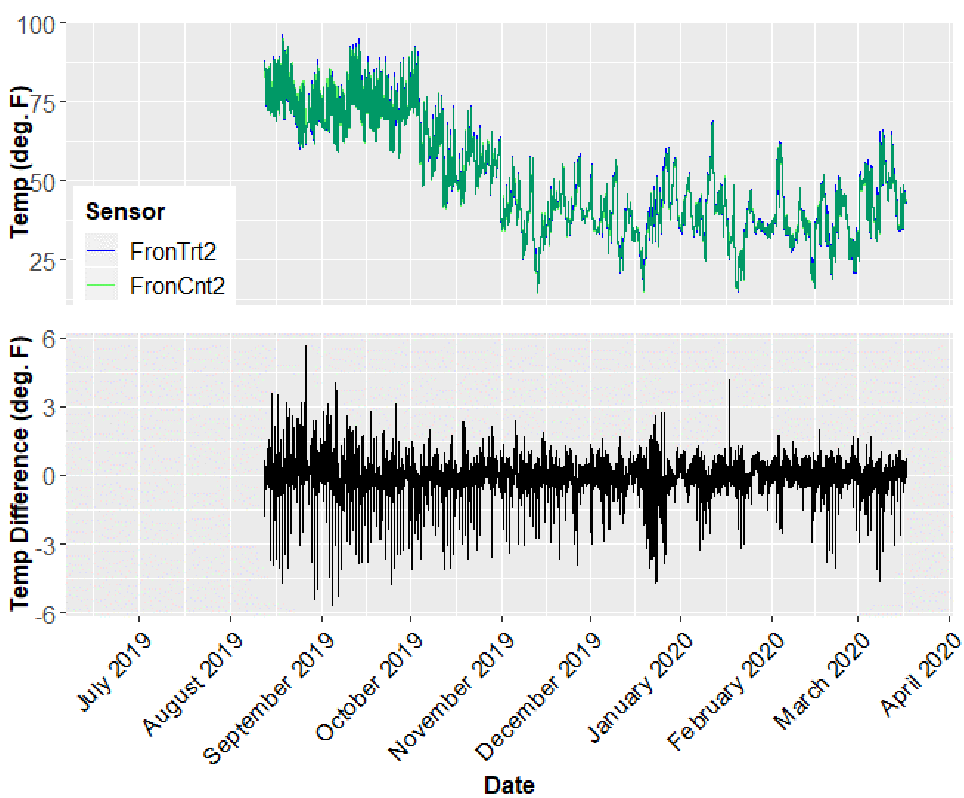
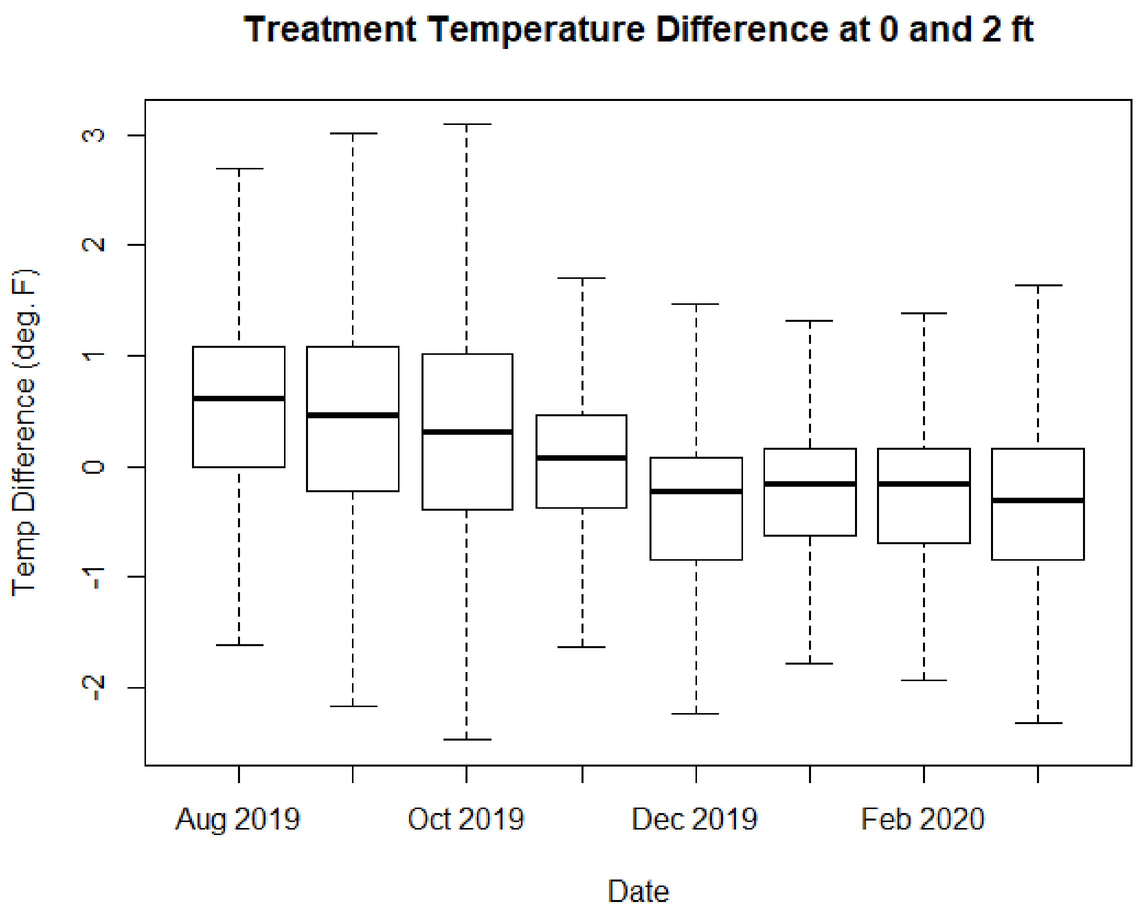


Table 32. Front Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.09	0.00	0.61	0.62	1.08	4.71
2019 09	-2.70	-0.23	0.47	0.46	1.08	5.10
2019 10	-2.71	-0.39	0.31	0.36	1.01	4.94
2019 11	-2.86	-0.38	0.08	0.06	0.47	4.33
2019 12	-5.02	-0.85	-0.23	-0.44	0.08	2.24
2020 01	-2.71	-0.62	-0.15	-0.24	0.16	2.24
2020 02	-3.09	-0.70	-0.15	-0.33	0.16	3.63
2020 03	-2.55	-0.85	-0.31	-0.32	0.16	4.09

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



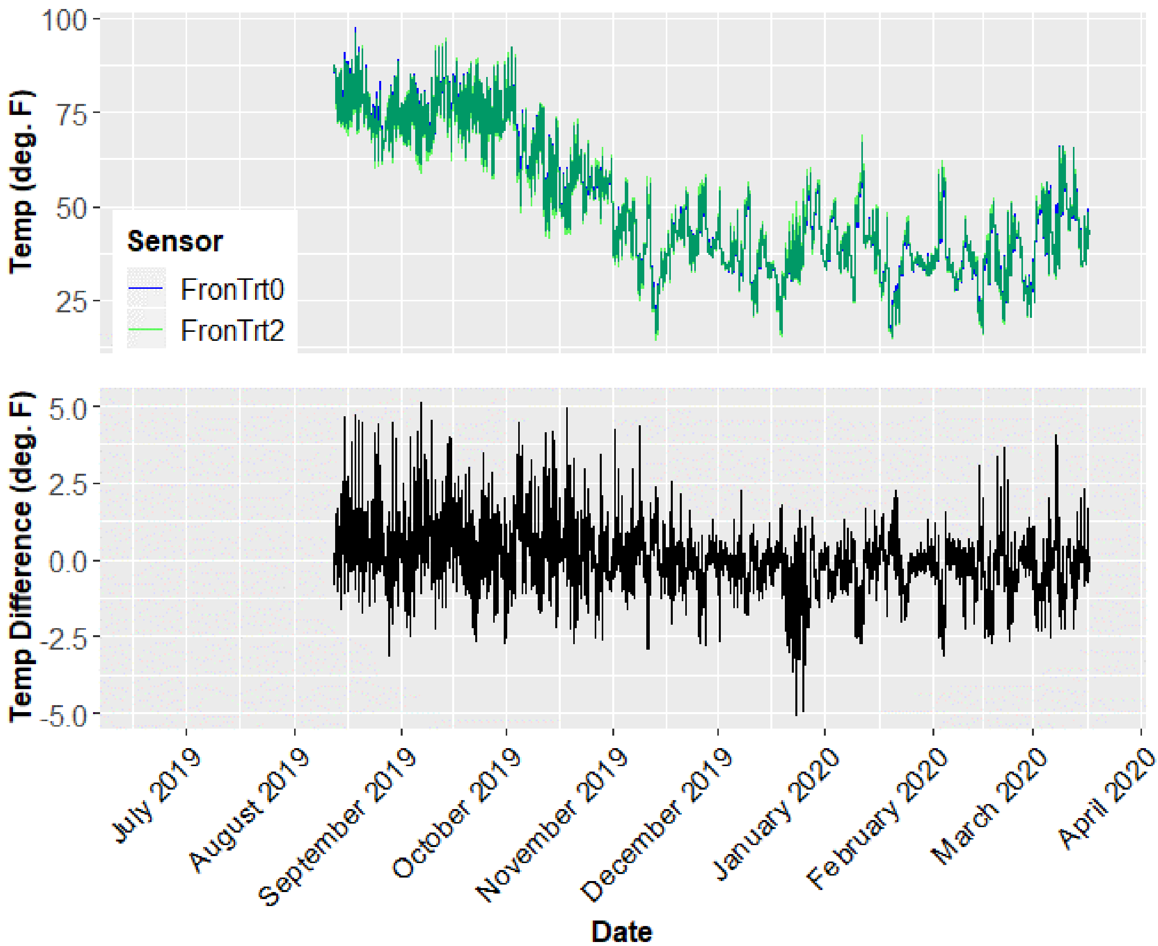
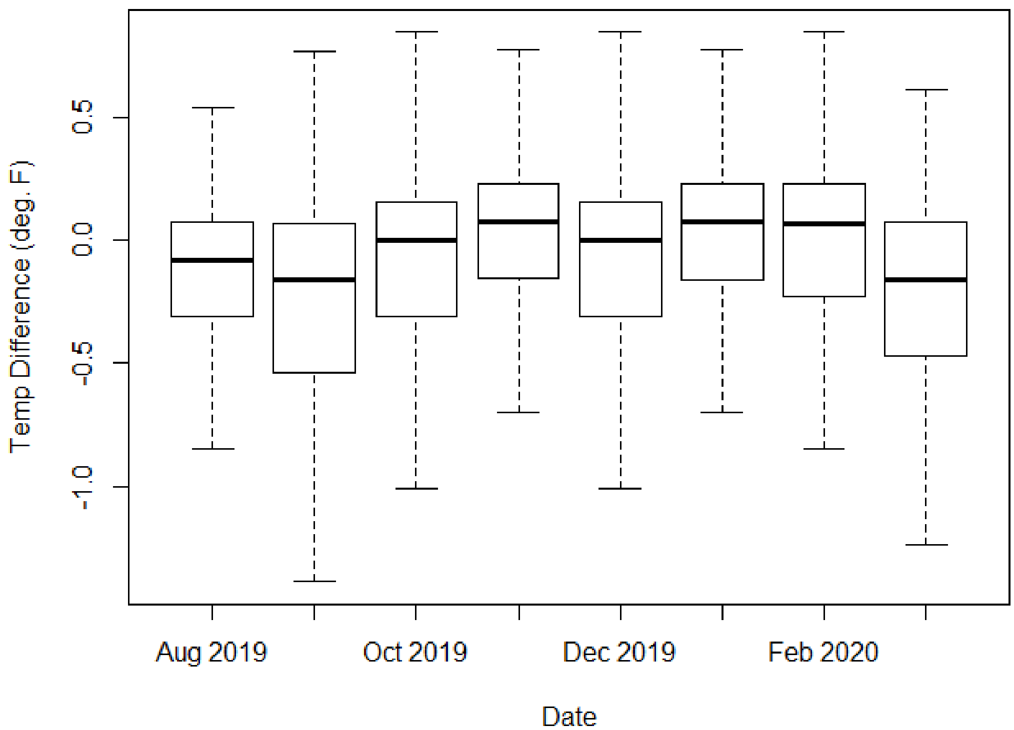


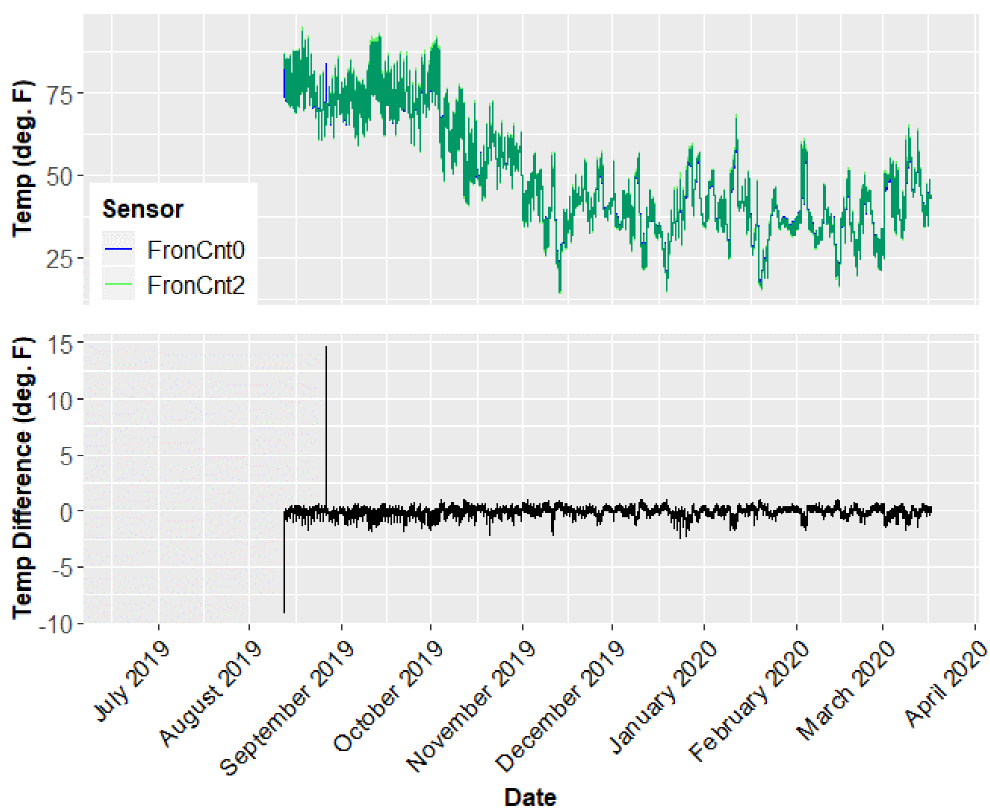
Table 33. Front Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-9.04	-0.31	-0.08	-0.10	0.08	14.60
2019 09	-1.93	-0.54	-0.16	-0.26	0.07	0.77
2019 10	-2.08	-0.31	0.00	-0.10	0.16	0.93
2019 11	-2.17	-0.15	0.08	0.03	0.23	1.00
2019 12	-2.39	-0.31	0.00	-0.13	0.16	1.00
2020 01	-1.78	-0.16	0.08	-0.02	0.23	1.01
2020 02	-1.77	-0.23	0.07	-0.03	0.23	0.93
2020 03	-1.70	-0.47	-0.16	-0.23	0.08	0.62

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Control Temperature Difference at 0 and 2 ft



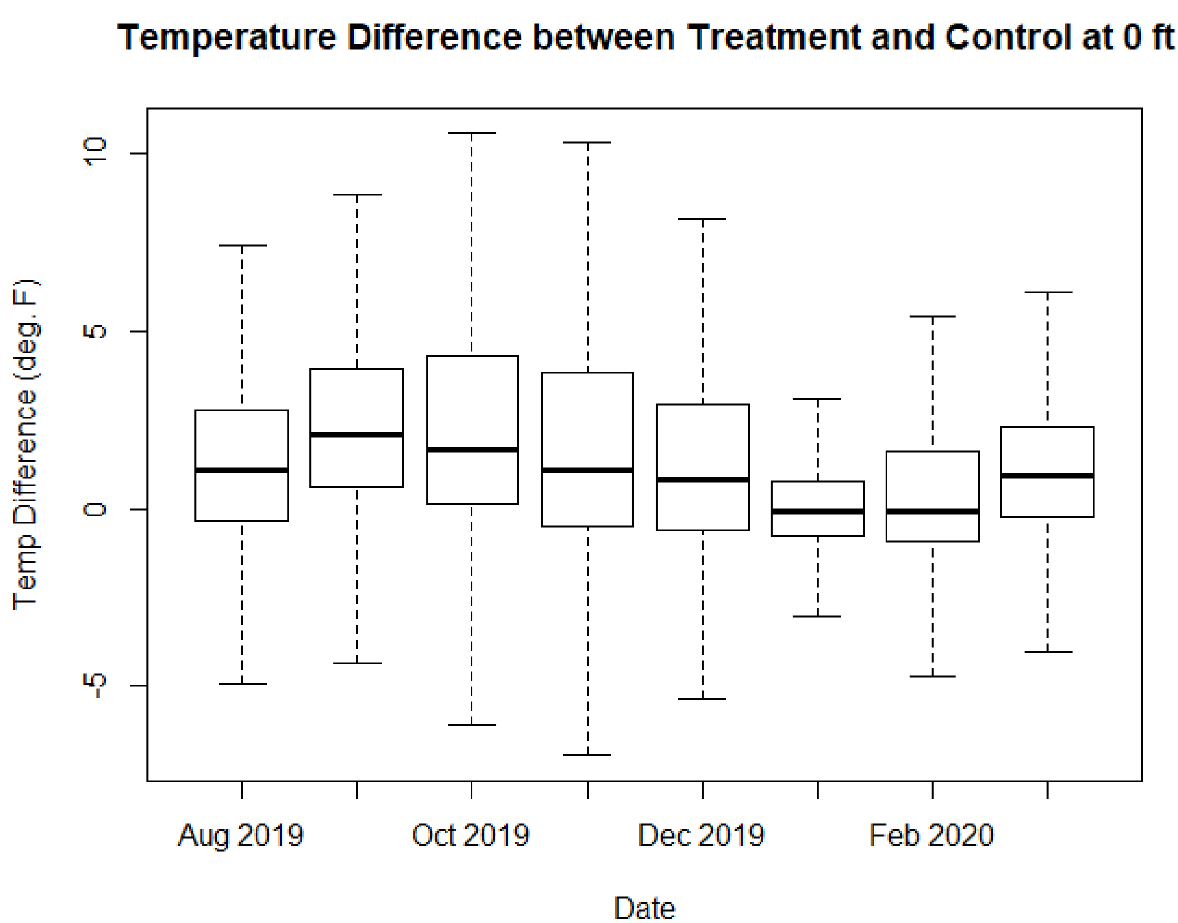


Glenmont

Table 34. Glenmont Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	--	--	--	--	--	--
2019 08	-9.73	-0.31	1.08	1.09	2.78	10.35
2019 09	-11.12	0.62	2.08	2.22	3.93	15.29
2019 10	-8.34	0.15	1.70	2.12	4.33	13.36
2019 11	-9.11	-0.47	1.08	1.58	3.86	11.51
2019 12	-5.33	-0.61	0.84	1.51	2.93	9.73
2020 01	-8.27	-0.77	-0.08	0.27	0.77	8.18
2020 02	-8.88	-0.93	-0.08	0.72	1.63	13.98
2020 03	-7.18	-0.23	0.92	1.04	2.32	8.19

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



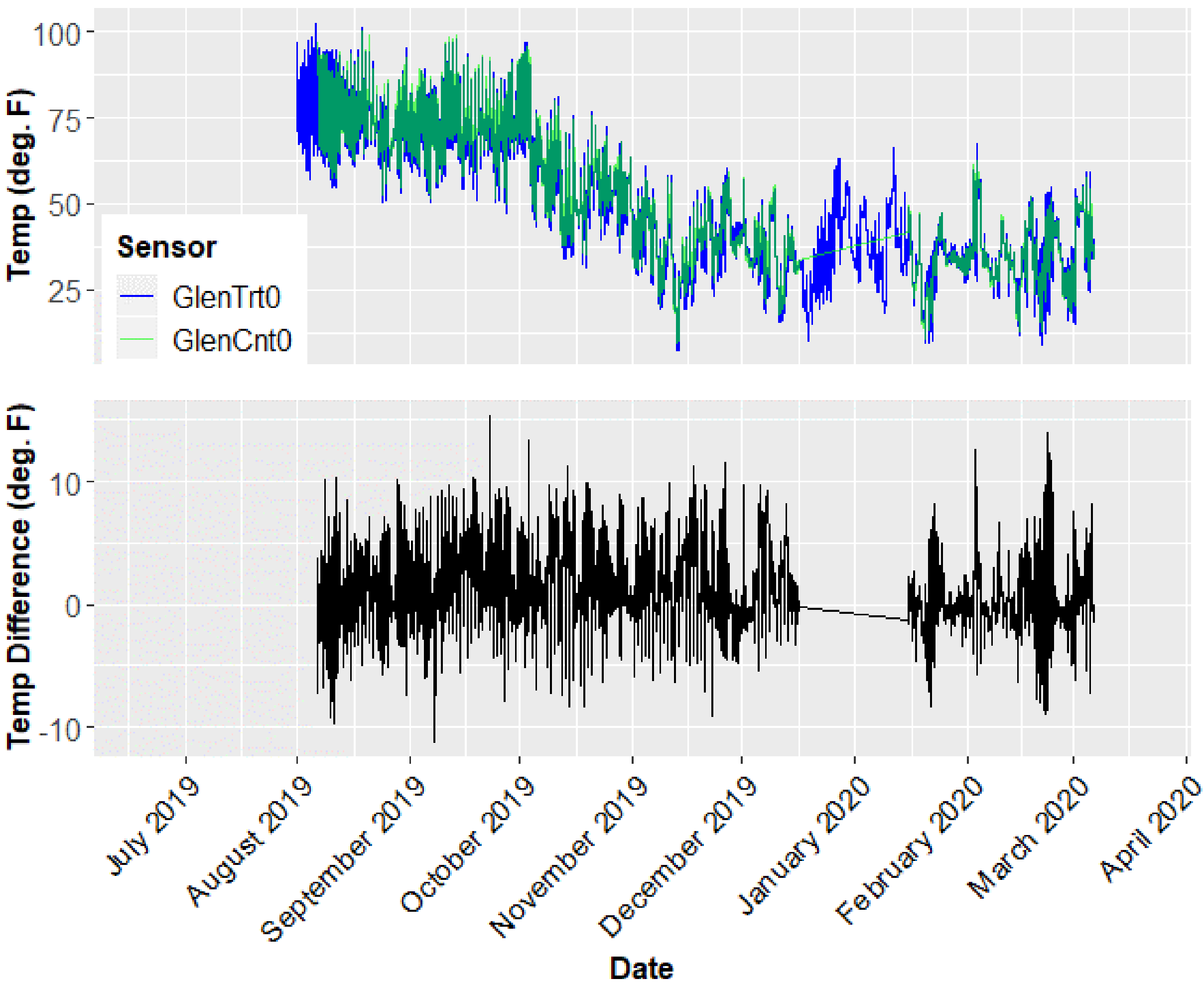
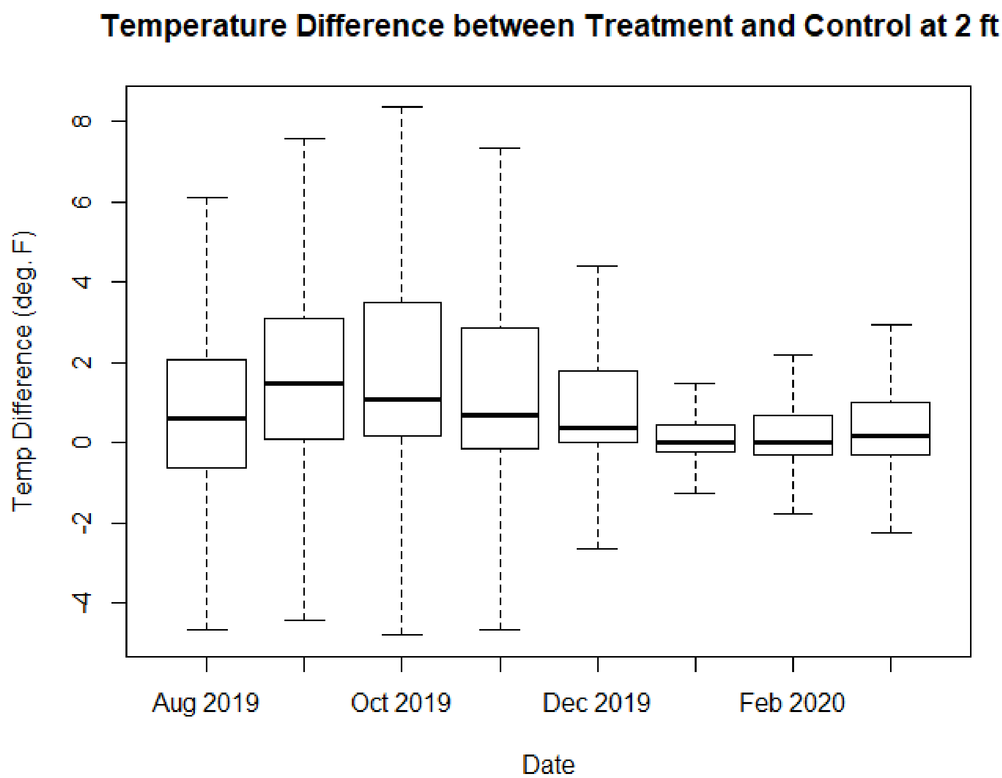


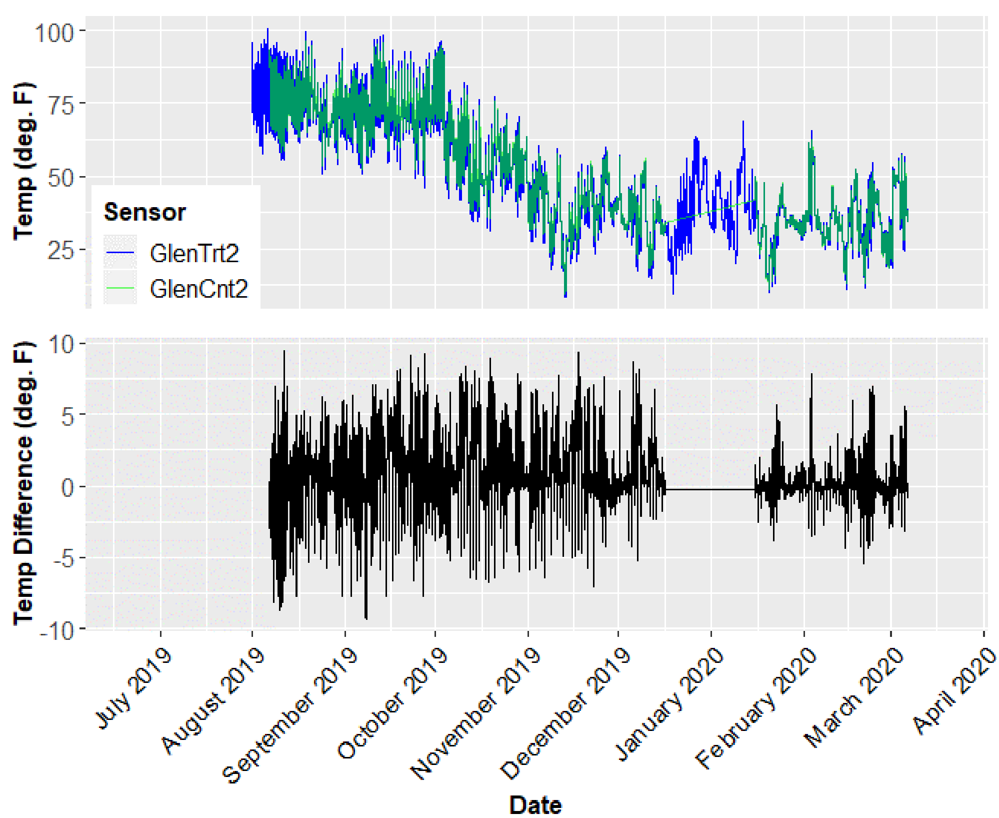
Table 35. Glenmont Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	--	--	--	--	--	--
2019 08	-8.72	-0.62	0.62	0.53	2.08	9.42
2019 09	-9.27	0.07	1.47	1.44	3.09	9.27
2019 10	-6.72	0.15	1.08	1.62	3.48	8.96
2019 11	-7.10	-0.15	0.69	1.24	2.85	9.35
2019 12	-5.25	0.00	0.38	1.13	1.78	8.65
2020 01	-3.78	-0.23	0.00	0.27	0.46	5.71
2020 02	-5.48	-0.31	0.00	0.39	0.70	7.80
2020 03	-3.17	-0.31	0.16	0.47	1.01	5.56

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Temperature Difference between Treatment and Control at 2 ft
Temp Difference (deg. F)
8
6
4
2
0
-2
-4
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date

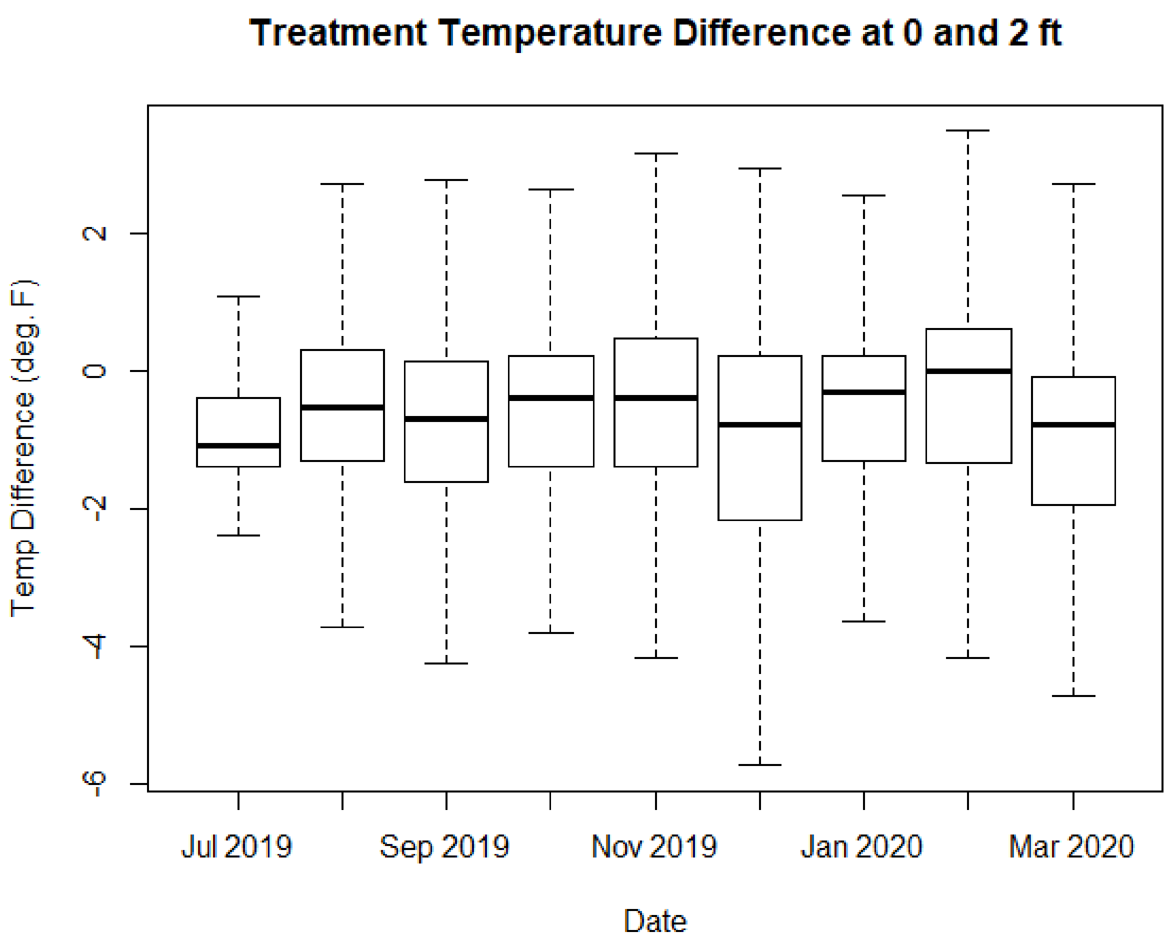


Temp (deg. F)
100
75
50
25
Sensor
GlenTrt2
GlenCnt2
Temp Difference (deg. F)
10
5
0
-5
-10
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Table 36. Glenmont Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-2.39	-1.39	-1.09	-0.77	-0.38	1.85
2019 08	-3.79	-1.31	-0.54	-0.33	0.31	5.63
2019 09	-5.40	-1.62	-0.69	-0.68	0.15	5.26
2019 10	-9.04	-1.39	-0.38	-0.61	0.23	5.33
2019 11	-5.33	-1.39	-0.38	-0.49	0.46	4.86
2019 12	-11.66	-2.16	-0.77	-1.17	0.23	2.94
2020 01	-6.80	-1.31	-0.31	-0.51	0.23	5.64
2020 02	-9.27	-1.32	0.00	-0.51	0.62	5.71
2020 03	-5.33	-1.93	-0.77	-0.82	-0.07	4.64

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



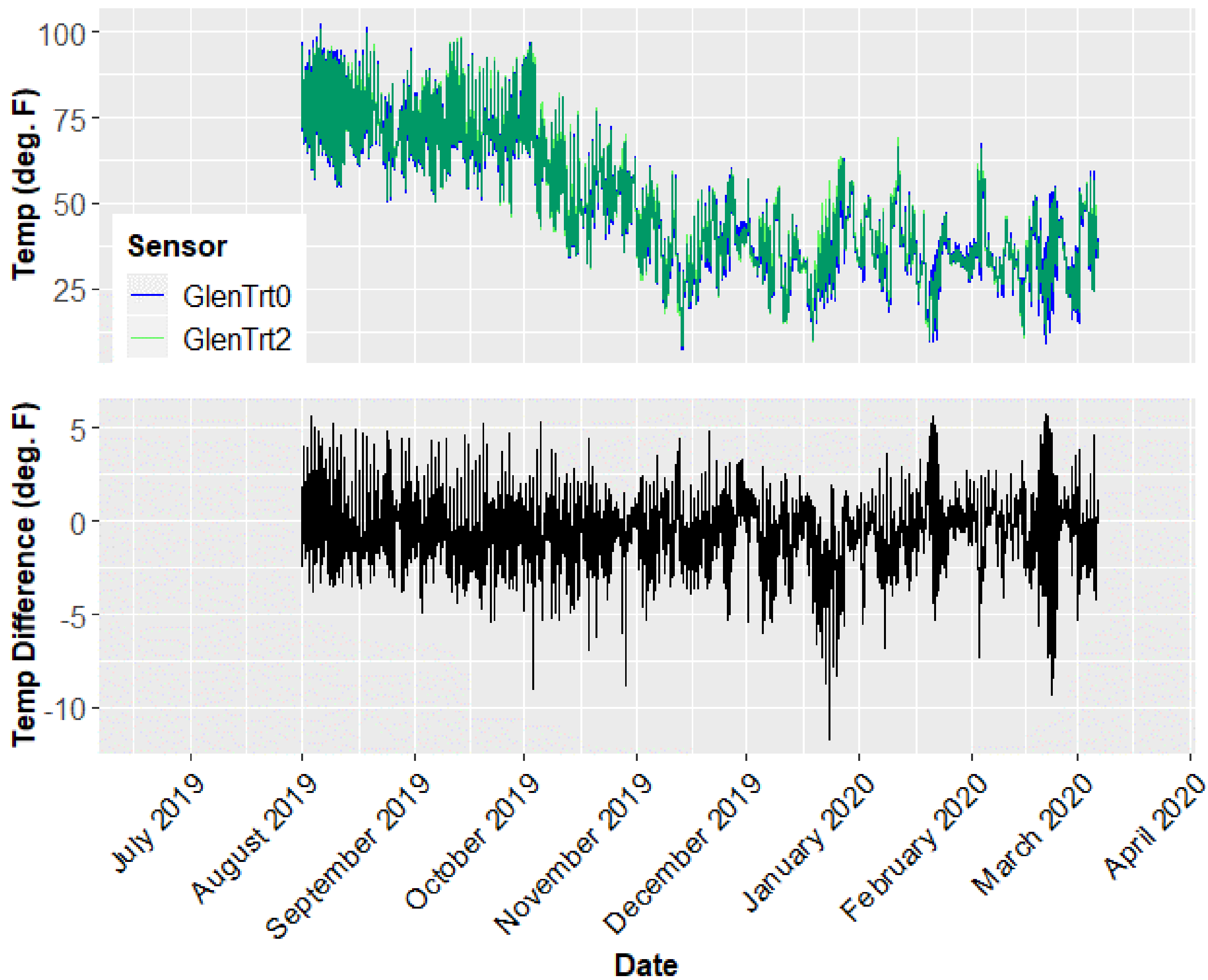
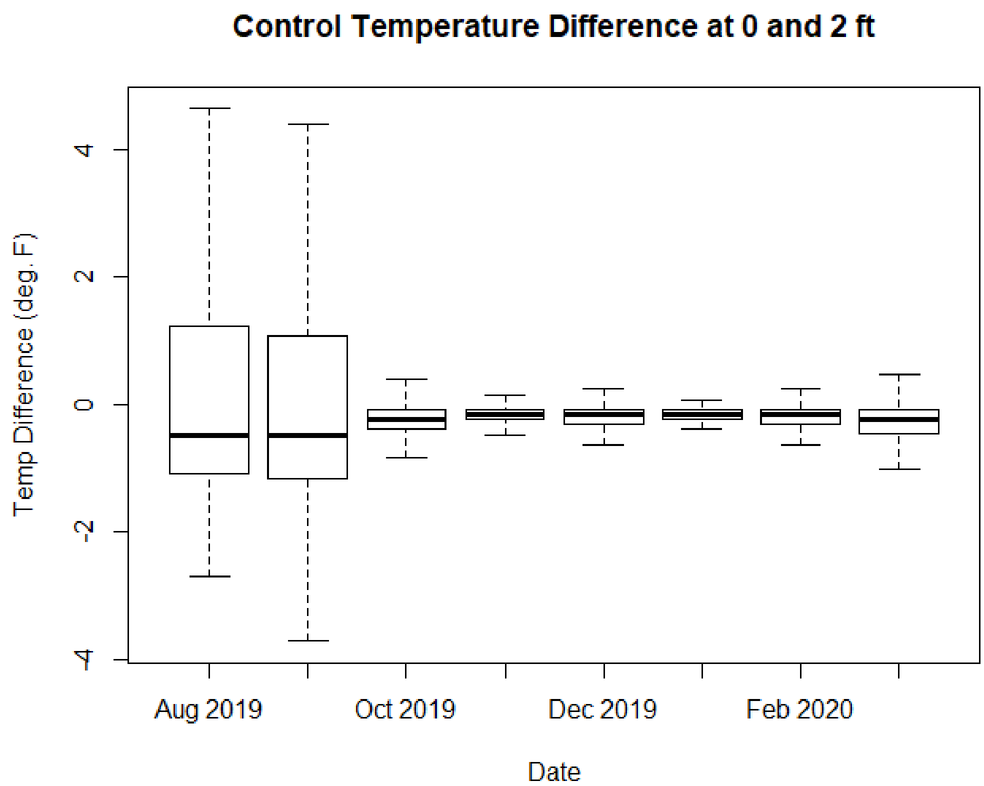
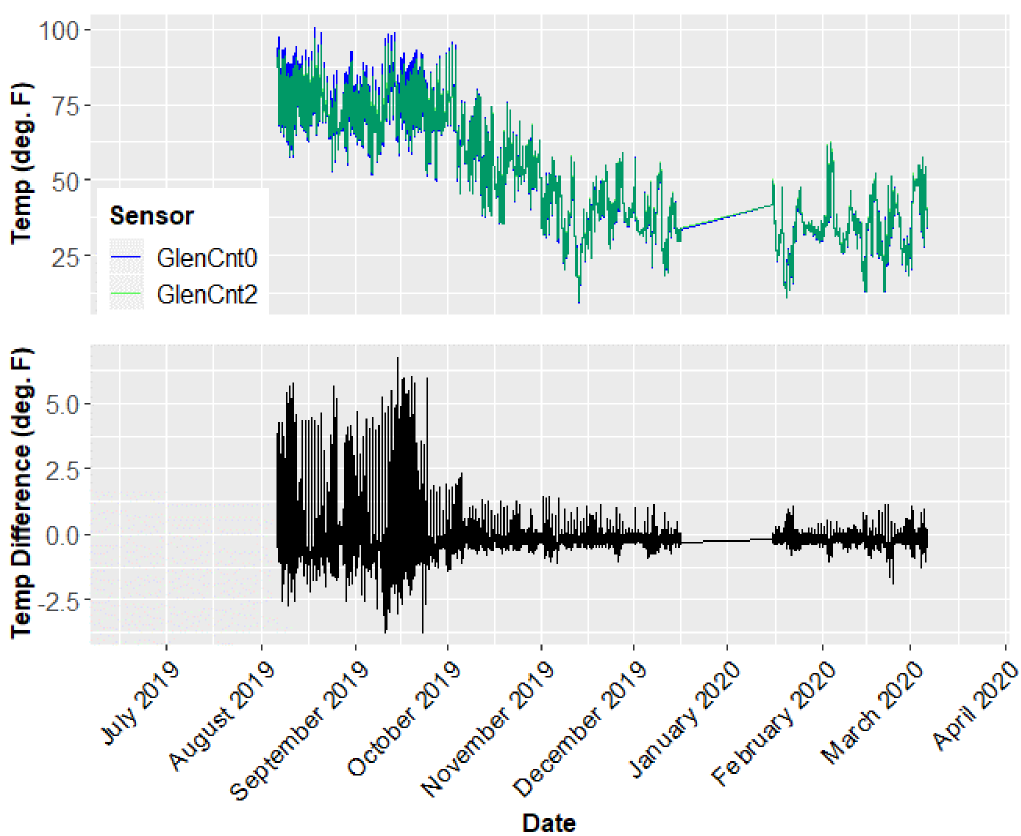


Table 37. Glenmont Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	--	--	--	--	--	--
2019 08	-2.70	-1.08	-0.47	0.20	1.23	5.79
2019 09	-3.71	-1.15	-0.47	0.11	1.08	6.72
2019 10	-1.32	-0.38	-0.23	-0.11	-0.07	2.32
2019 11	-1.08	-0.24	-0.16	-0.14	-0.08	1.47
2019 12	-0.93	-0.31	-0.16	-0.18	-0.08	1.16
2020 01	-0.77	-0.23	-0.15	-0.14	-0.08	1.08
2020 02	-1.86	-0.31	-0.16	-0.18	-0.07	1.16
2020 03	-1.24	-0.46	-0.23	-0.25	-0.08	1.08

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
4
2
0
-2
-4
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date

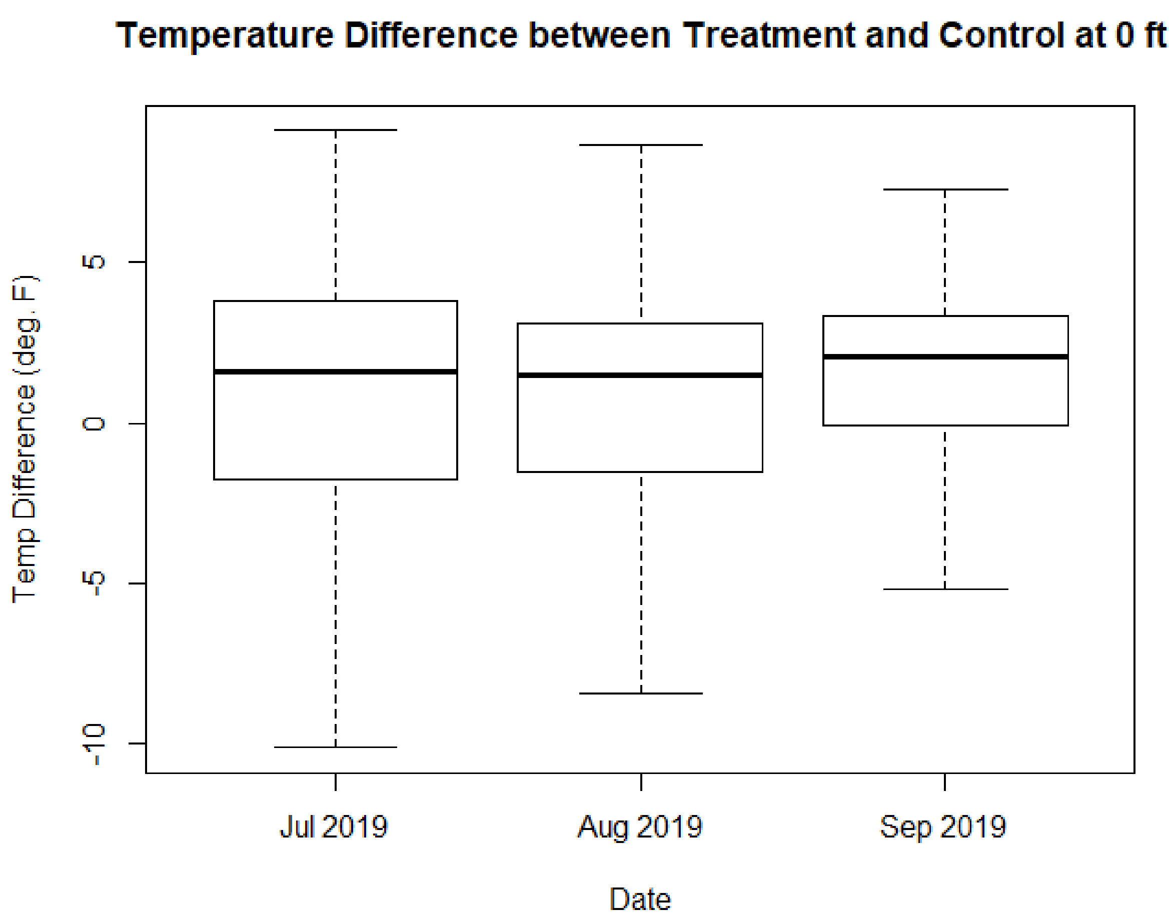

Temp (deg. F)
100
75
50
25
Sensor
GlenCnt0
GlenCnt2
Temp Difference (deg. F)
5.0
2.5
0.0
-2.5
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Howlett

Table 38. Howlett Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-12.20	-1.78	1.62	0.83	3.78	9.11
2019 08	-15.21	-1.54	1.47	0.29	3.09	8.65
2019 09	-9.50	-0.08	2.09	1.20	3.32	7.26
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	--	--	--	--	--	--
2020 02	--	--	--	--	--	--

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



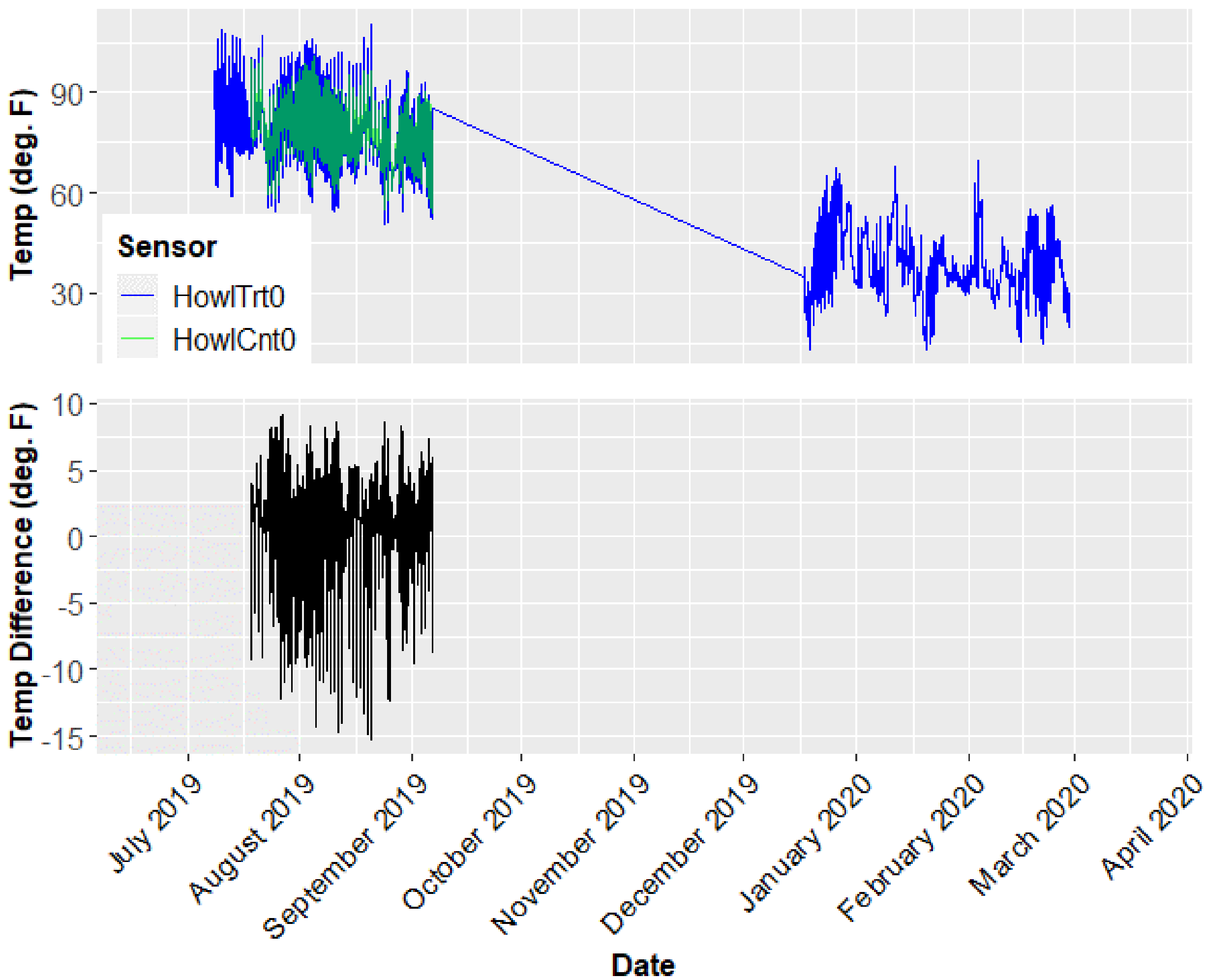
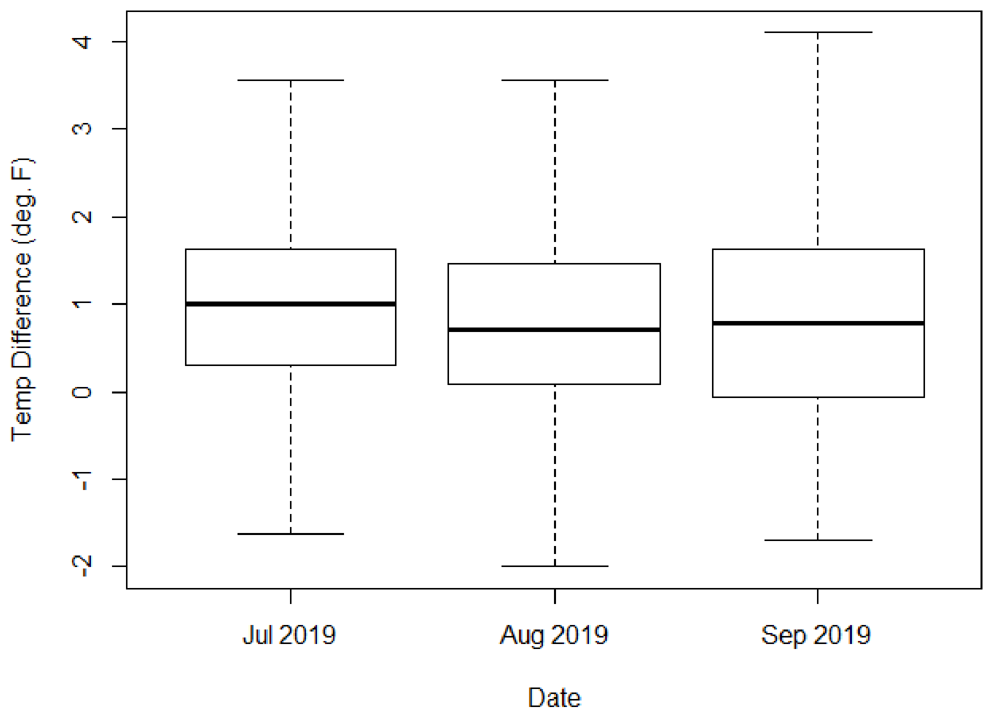


Table 39. Howlett Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-5.17	0.31	1.00	1.22	1.62	9.50
2019 08	-3.01	0.08	0.70	1.05	1.47	10.11
2019 09	-1.70	-0.07	0.78	1.32	1.62	10.11
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	--	--	--	--	--	--
2020 02	--	--	--	--	--	--

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



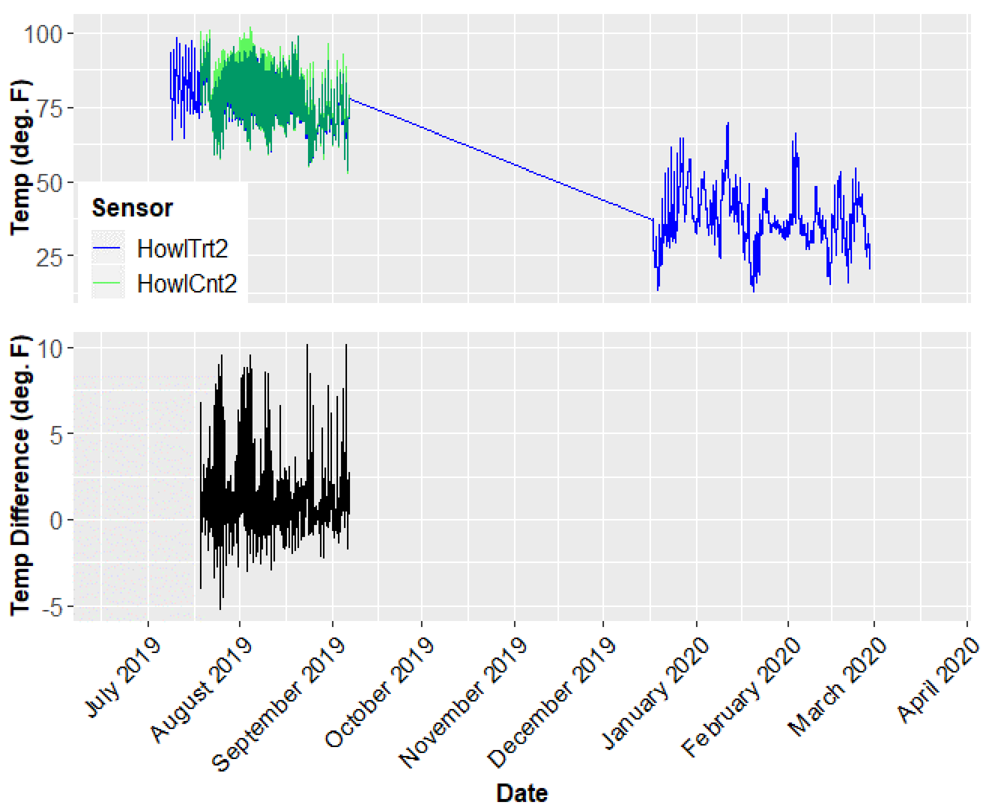
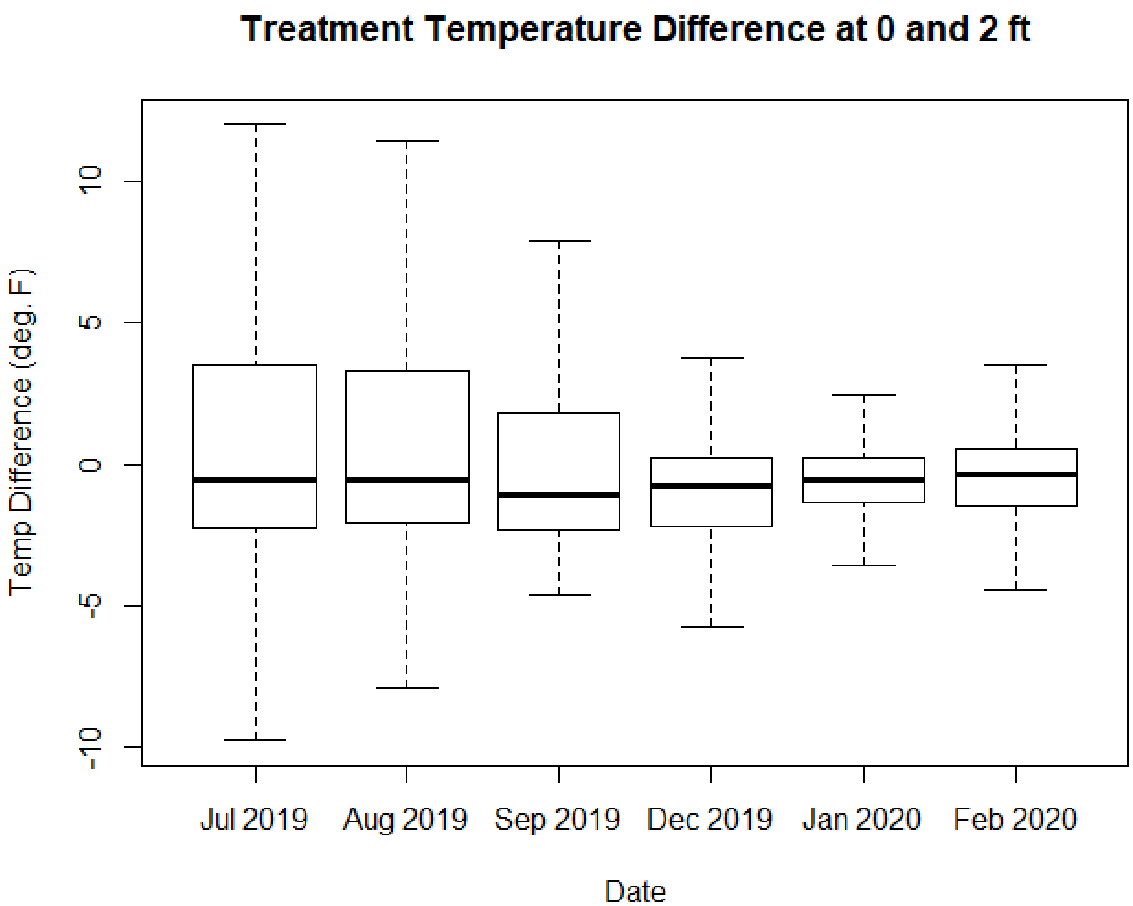


Table 40. Howlett Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-9.73	-2.24	-0.54	0.80	3.47	14.06
2019 08	-7.88	-2.09	-0.54	0.82	3.32	15.21
2019 09	-4.64	-2.31	-1.08	0.23	1.77	9.89
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	-10.66	-2.16	-0.77	-0.93	0.24	7.87
2020 01	-5.02	-1.31	-0.54	-0.33	0.23	9.89
2020 02	-7.80	-1.46	-0.39	-0.29	0.54	10.34

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



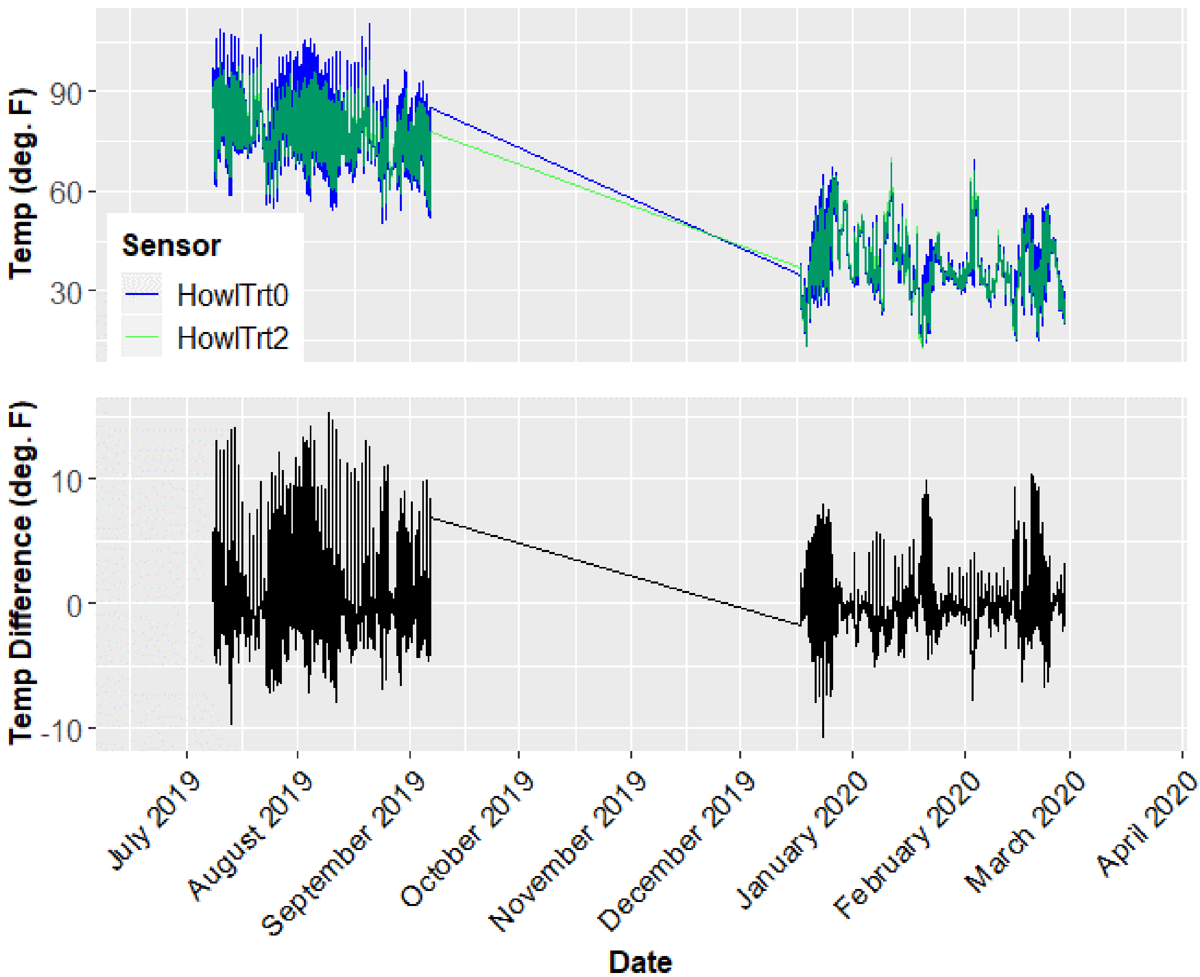
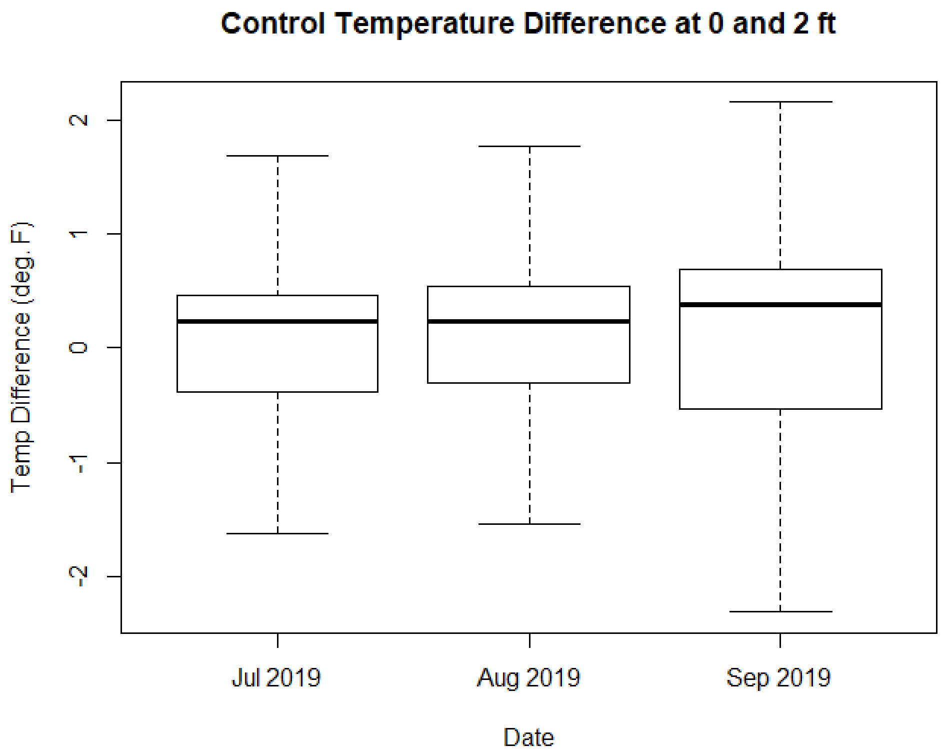


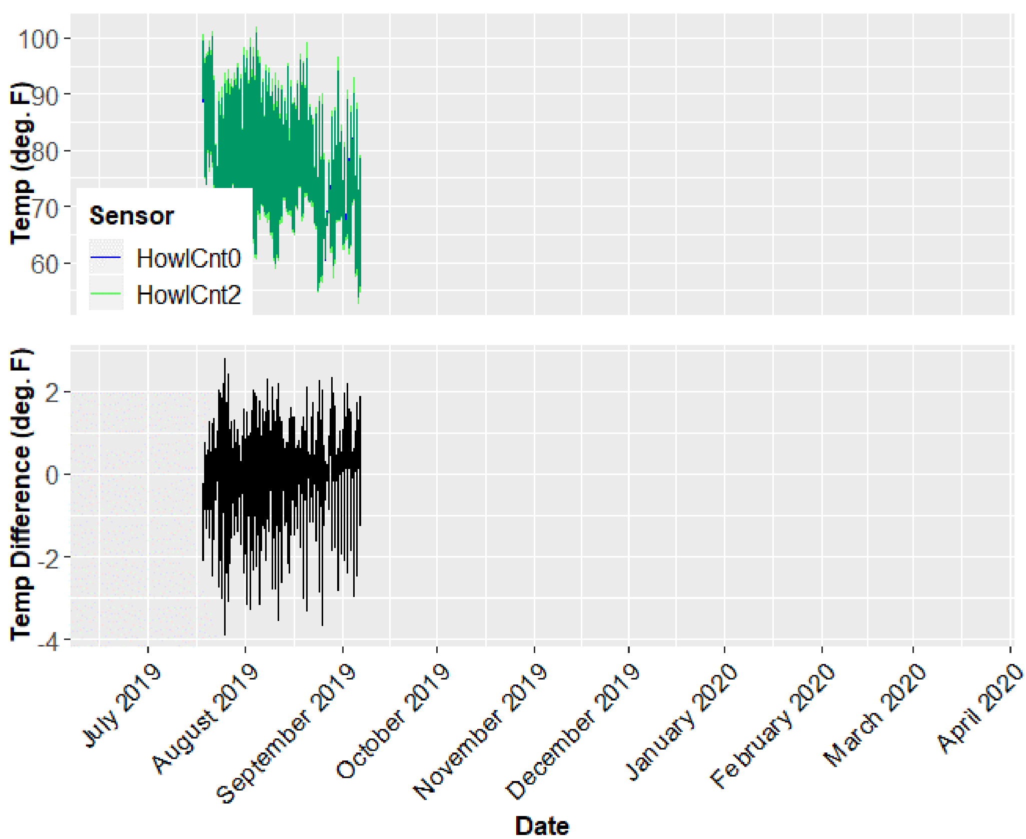
Table 41. Howlett Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-3.86	-0.39	0.23	0.06	0.47	2.78
2019 08	-3.63	-0.31	0.23	0.07	0.54	2.32
2019 09	-2.94	-0.54	0.38	0.11	0.69	2.16
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	--	--	--	--	--	--
2020 02	--	--	--	--	--	--

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
2
1
0
-1
-2
Jul 2019
Aug 2019
Sep 2019
Date



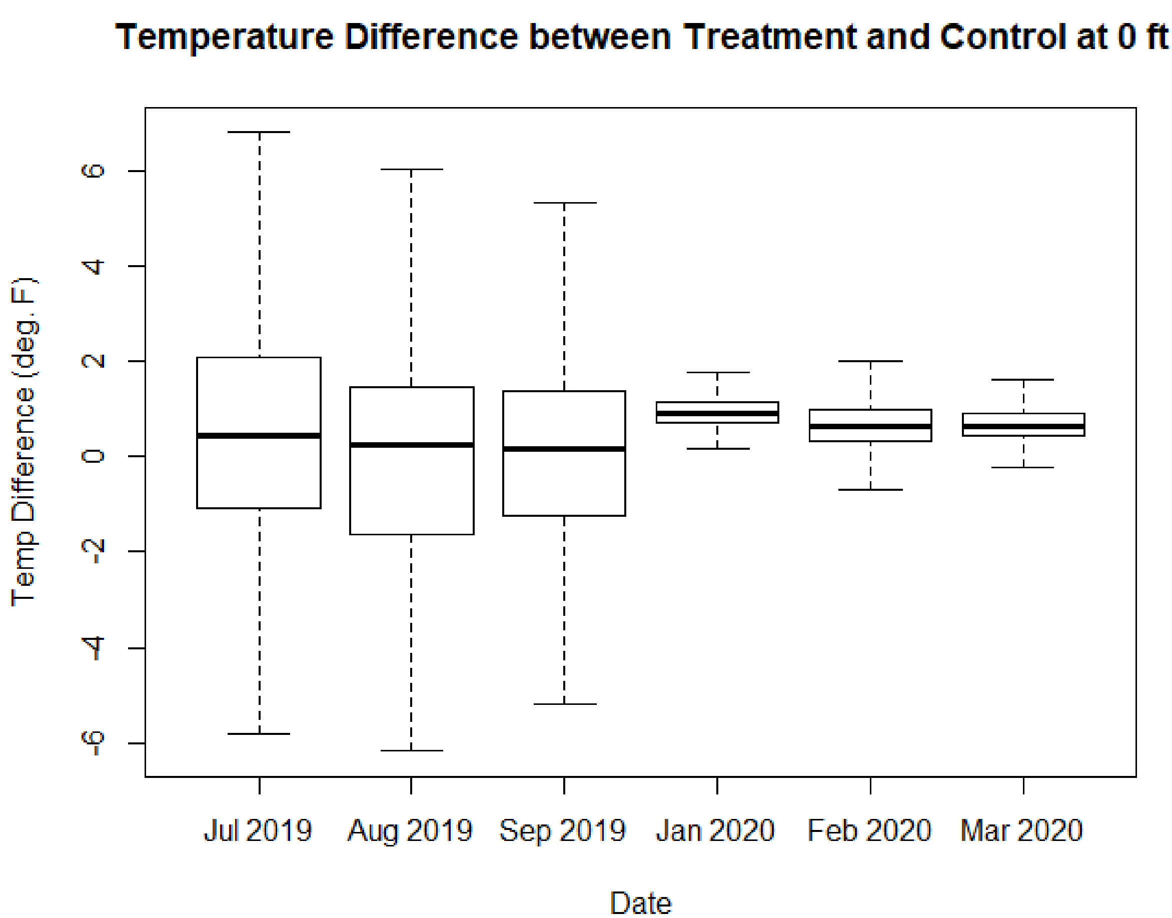
Temp (deg. F)
100
90
80
70
60
Sensor
HowlCnt0
HowlCnt2
Temp Difference (deg. F)
2
0
-2
-4
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Knowlton

Table 42. Knowlton Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-12.43	-1.08	0.46	0.32	2.08	13.51
2019 08	-12.75	-1.62	0.24	-0.28	1.46	17.30
2019 09	-11.66	-1.24	0.15	0.06	1.39	11.50
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	0.15	0.70	0.93	0.96	1.16	2.01
2020 02	-5.10	0.31	0.62	0.59	1.01	7.11
2020 03	-1.62	0.46	0.62	0.68	0.93	2.62

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



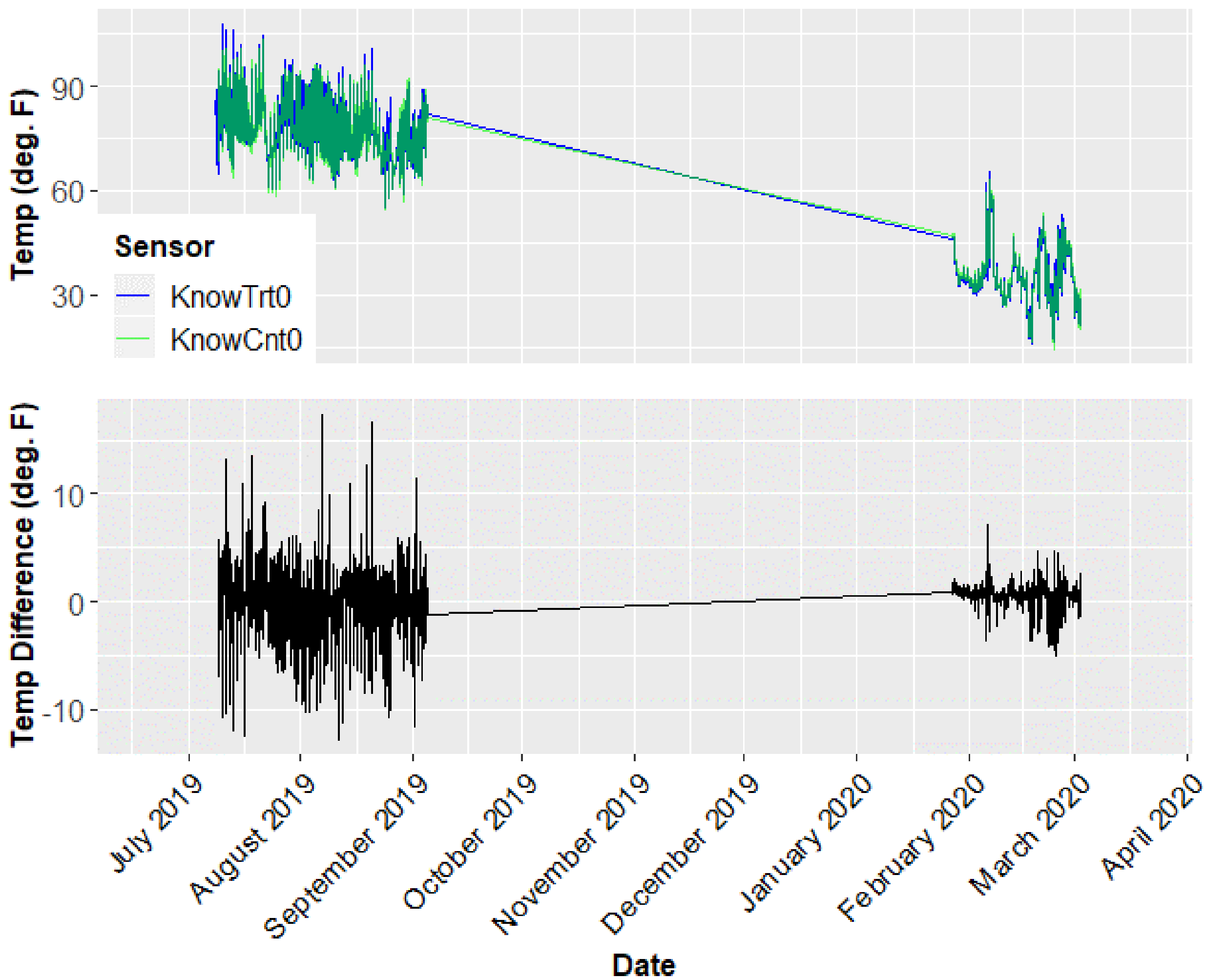
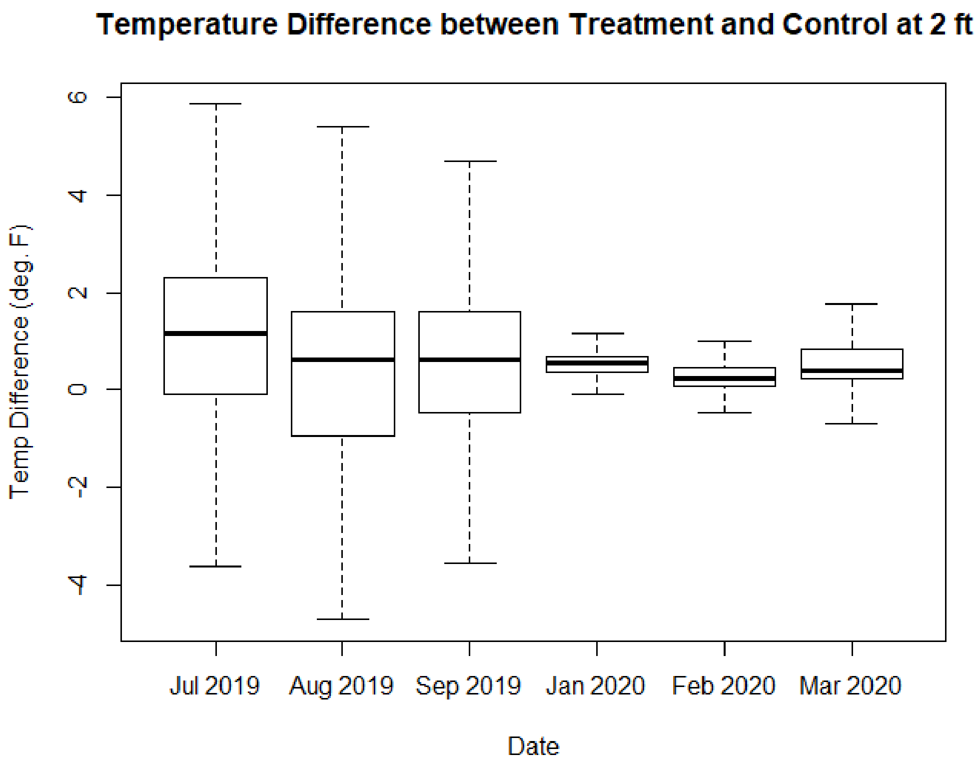


Table 43. Knowlton Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-7.49	-0.08	1.16	1.12	2.32	13.67
2019 08	-7.26	-0.93	0.62	0.31	1.62	17.45
2019 09	-6.18	-0.46	0.62	0.67	1.62	11.59
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-0.08	0.38	0.54	0.54	0.69	1.39
2020 02	-3.79	0.07	0.24	0.23	0.47	4.63
2020 03	-1.16	0.23	0.39	0.59	0.85	3.48

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Temperature Difference between Treatment and Control at 2 ft
Temp Difference (deg. F)
6
4
2
0
-2
-4
Jul 2019
Aug 2019
Sep 2019
Jan 2020
Feb 2020
Mar 2020
Date

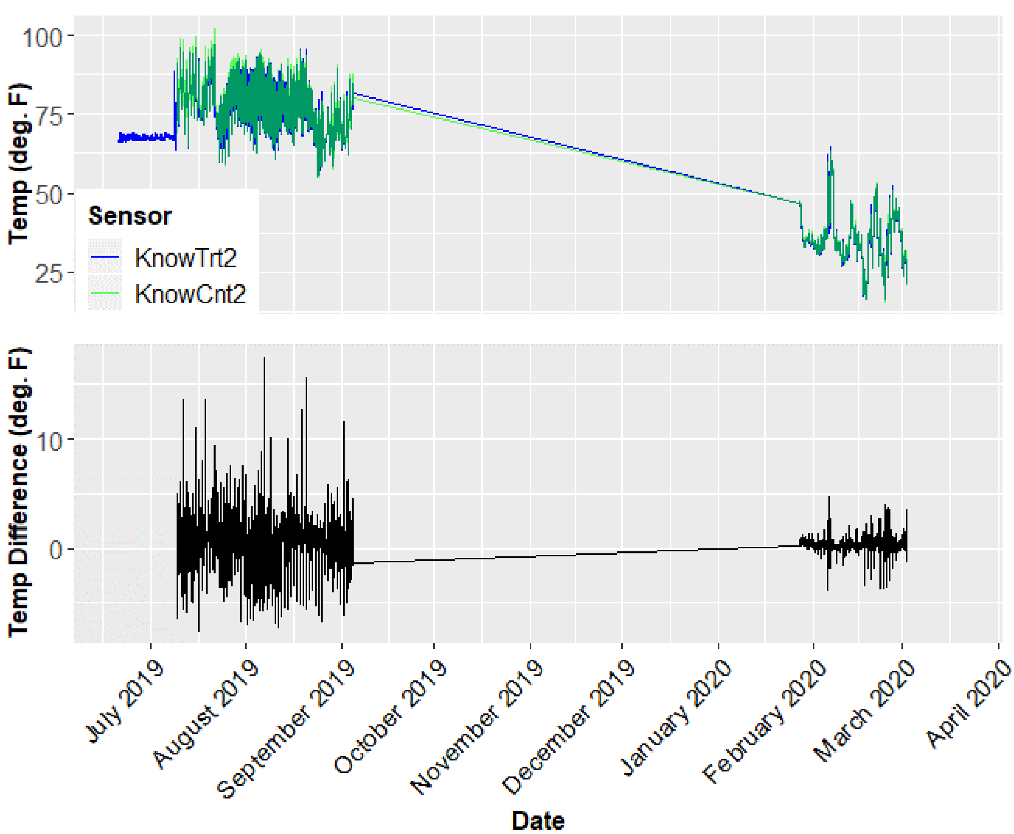
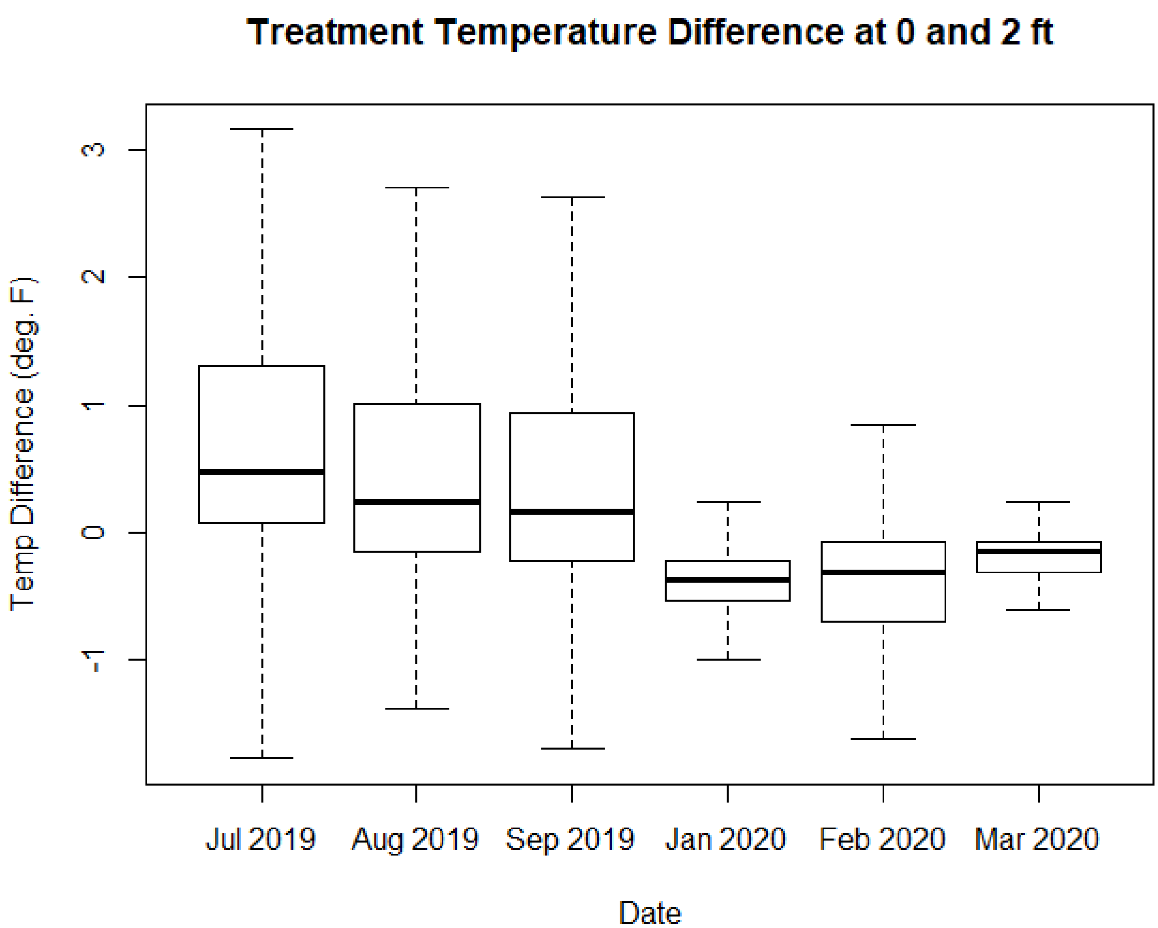

Temp (deg. F)
100
75
50
25
Sensor
KnowTrt2
KnowCnt2
Temp Difference (deg. F)
10
0
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Table 44. Knowlton Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-1.93	0.07	0.47	0.99	1.31	14.28
2019 08	-1.39	-0.15	0.23	0.65	1.01	8.34
2019 09	-1.70	-0.23	0.16	0.58	0.93	5.94
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-1.47	-0.54	-0.38	-0.39	-0.23	0.70
2020 02	-3.79	-0.70	-0.31	-0.41	-0.08	2.78
2020 03	-0.85	-0.31	-0.16	-0.21	-0.08	0.39

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



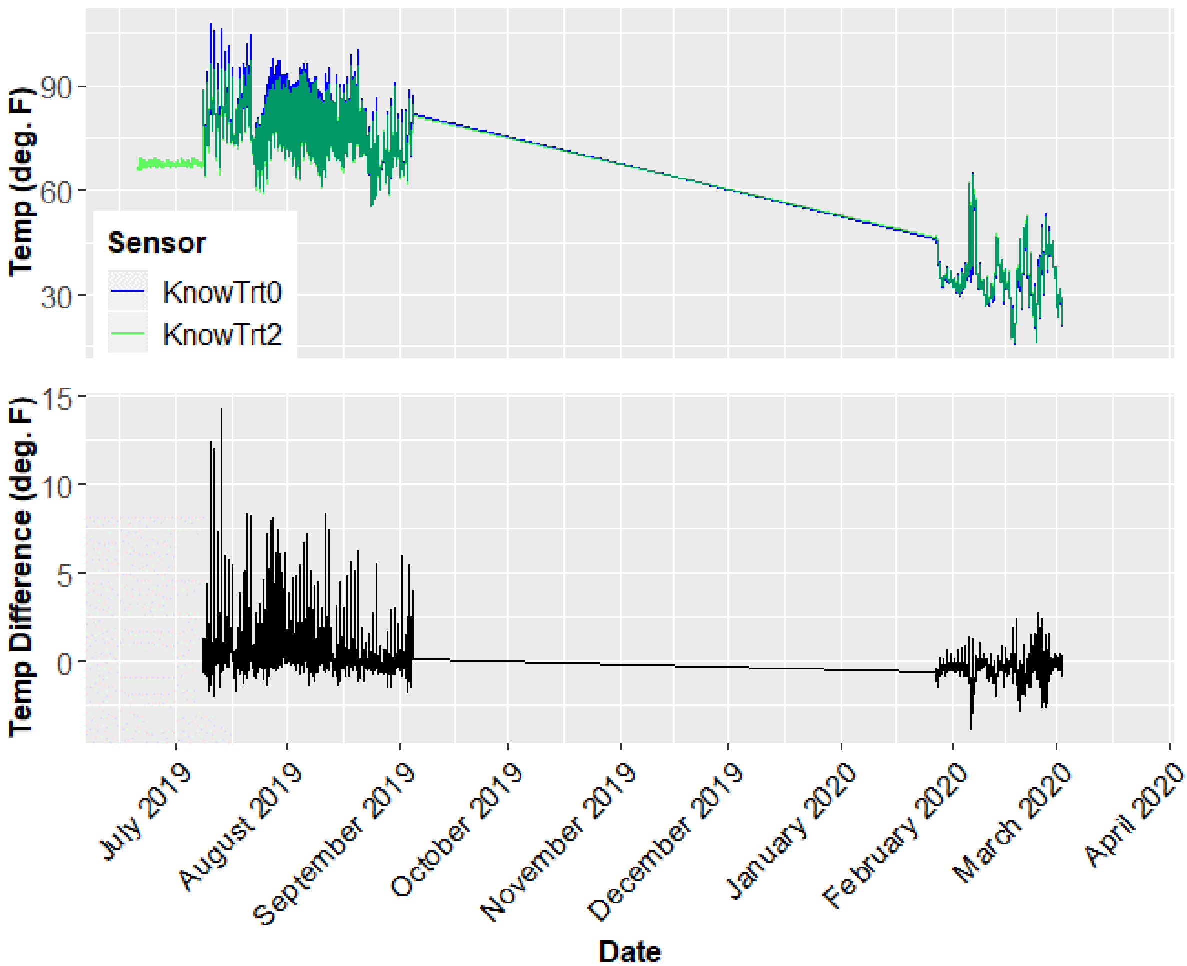
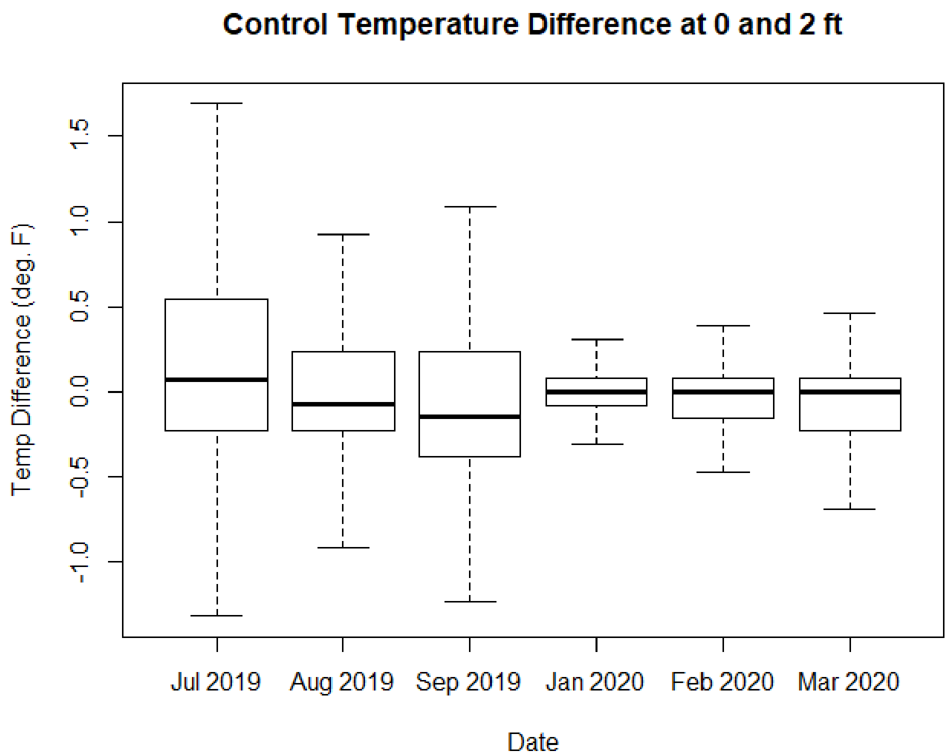
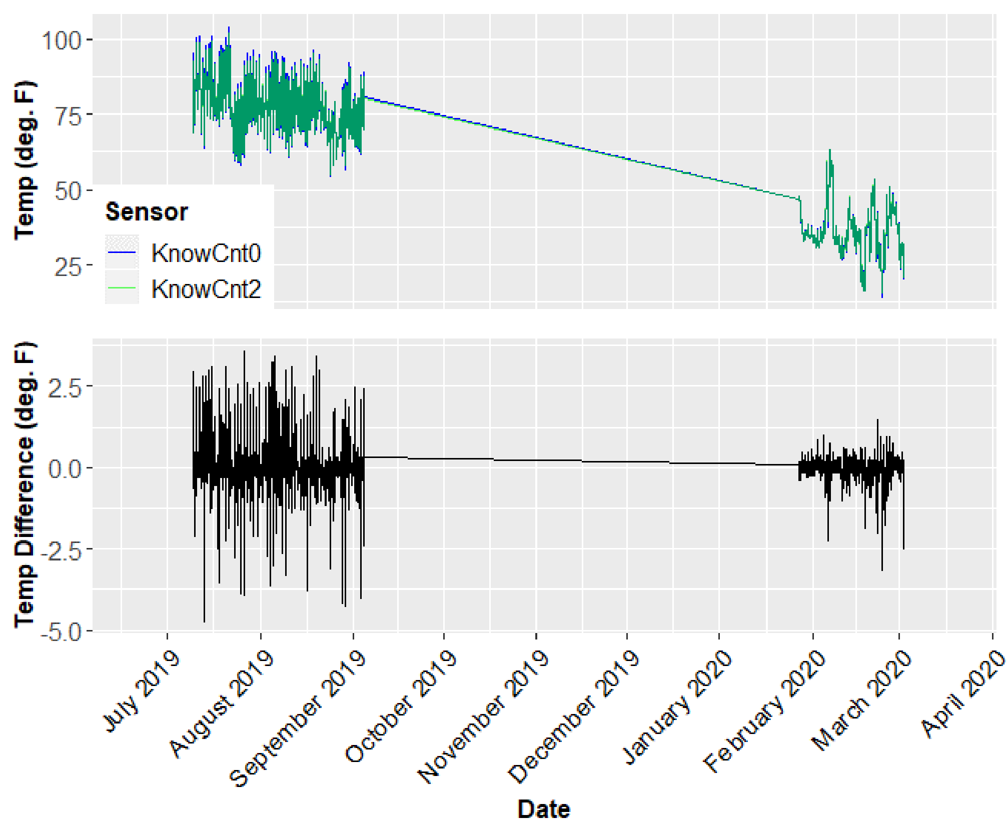


Table 45. Knowlton Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-4.71	-0.23	0.07	0.20	0.54	3.55
2019 08	-4.25	-0.23	-0.07	0.06	0.23	3.40
2019 09	-4.02	-0.38	-0.15	-0.03	0.23	2.48
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-0.39	-0.08	0.00	0.02	0.08	0.54
2020 02	-3.16	-0.16	0.00	-0.05	0.08	1.47
2020 03	-2.47	-0.23	0.00	-0.12	0.08	0.46

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
1.5
1.0
0.5
0.0
-0.5
-1.0
Jul 2019
Aug 2019
Sep 2019
Jan 2020
Feb 2020
Mar 2020
Date

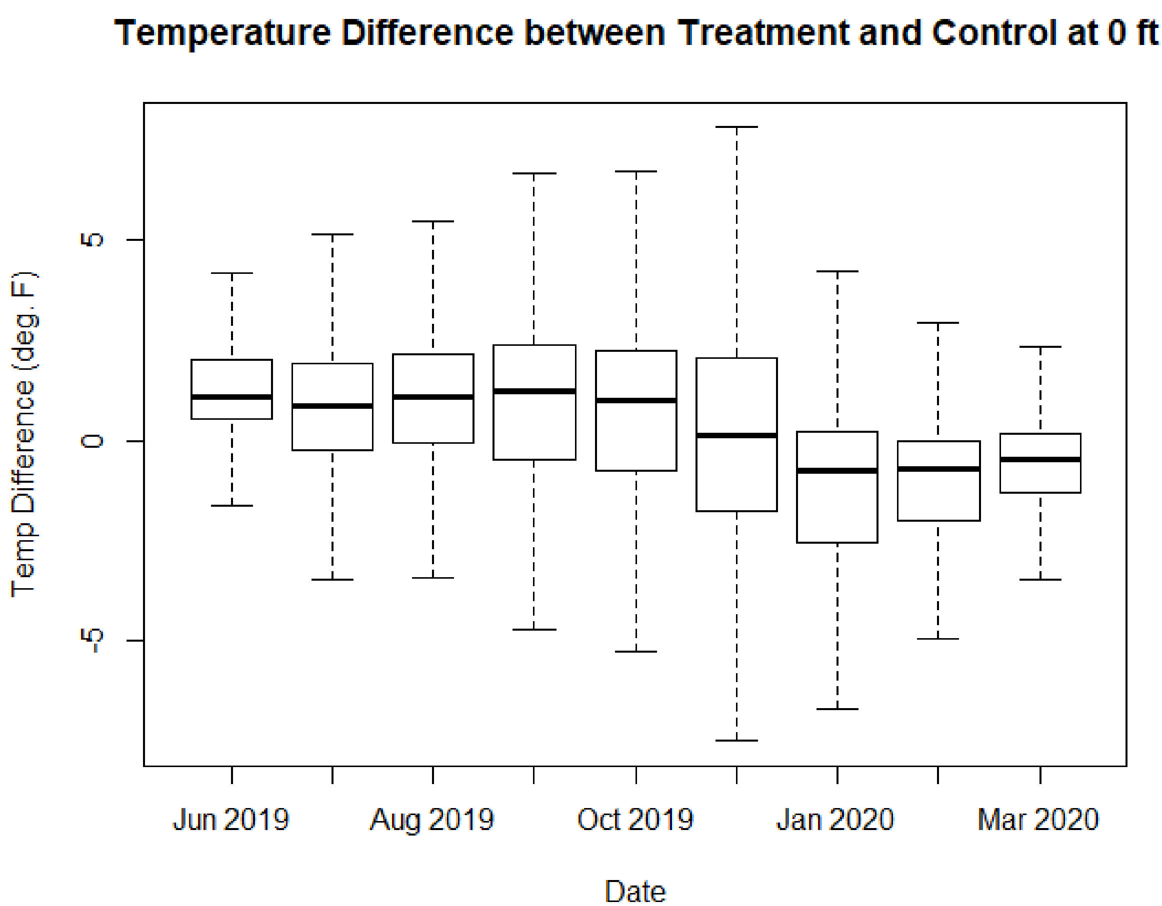

Temp (deg. F)
100
75
50
25
Sensor
KnowCnt0
KnowCnt2
Temp Difference (deg. F)
2.5
0.0
-2.5
-5.0
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Lazarus

Table 46. Lazarus Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-3.09	0.54	1.08	1.14	2.01	4.71
2019 07	-6.26	-0.23	0.85	0.70	1.93	7.18
2019 08	-6.49	-0.07	1.08	0.81	2.16	8.42
2019 09	-7.33	-0.46	1.24	0.90	2.39	8.50
2019 10	-7.80	-0.77	1.00	0.59	2.24	8.26
2019 11	Sensor Malfunction					
2019 12	-8.72	-1.77	0.15	0.21	2.08	9.96
2020 01	-10.58	-2.55	-0.77	-1.28	0.23	4.24
2020 02	-11.27	-2.00	-0.69	-1.18	0.00	4.71
2020 03	-7.80	-1.32	-0.47	-0.72	0.16	4.17

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



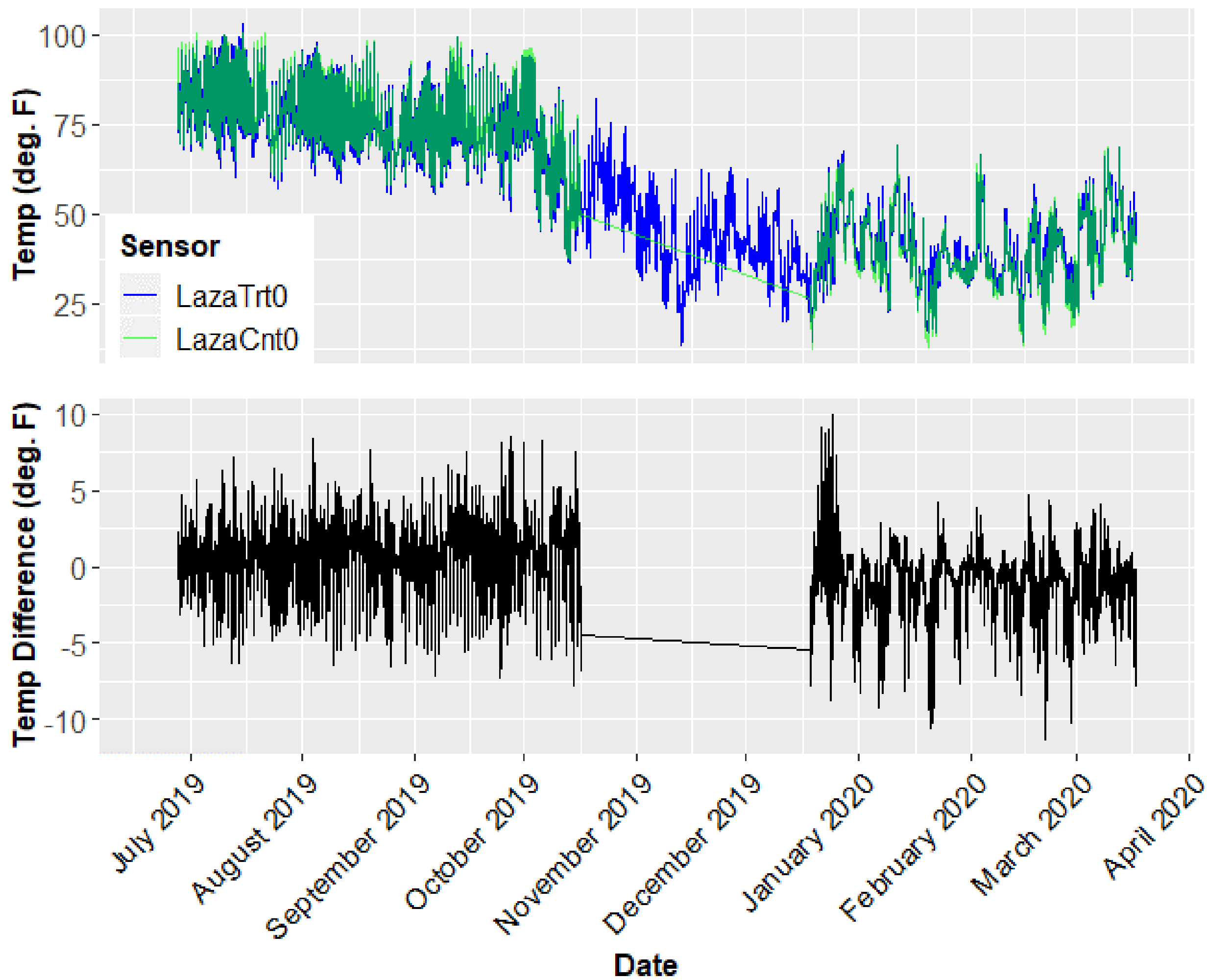
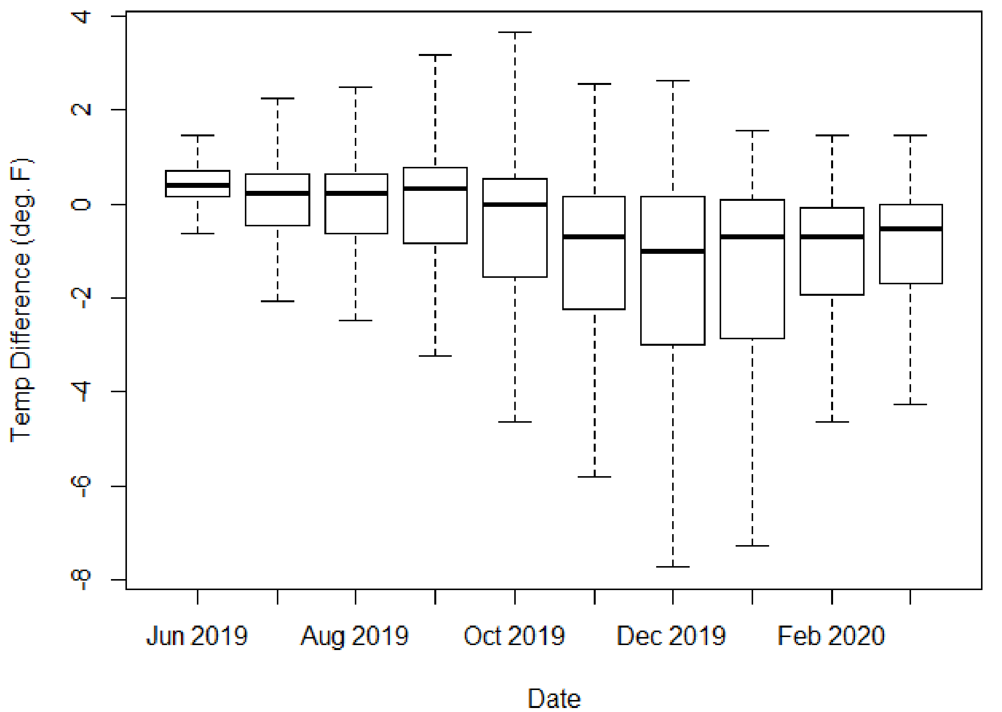


Table 47. Lazarus Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-3.55	0.15	0.39	0.27	0.70	2.78
2019 07	-5.33	-0.46	0.24	0.00	0.62	3.40
2019 08	-6.02	-0.62	0.23	-0.07	0.62	6.10
2019 09	-6.95	-0.85	0.31	-0.10	0.77	3.32
2019 10	-8.34	-1.54	0.00	-0.66	0.54	3.78
2019 11	-12.20	-2.24	-0.70	-1.49	0.15	2.55
2019 12	-12.12	-3.01	-1.01	-1.69	0.15	2.63
2020 01	-11.51	-2.86	-0.70	-1.72	0.08	1.55
2020 02	-13.05	-1.93	-0.70	-1.59	-0.08	1.47
2020 03	-8.96	-1.70	-0.54	-1.13	0.00	1.47

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



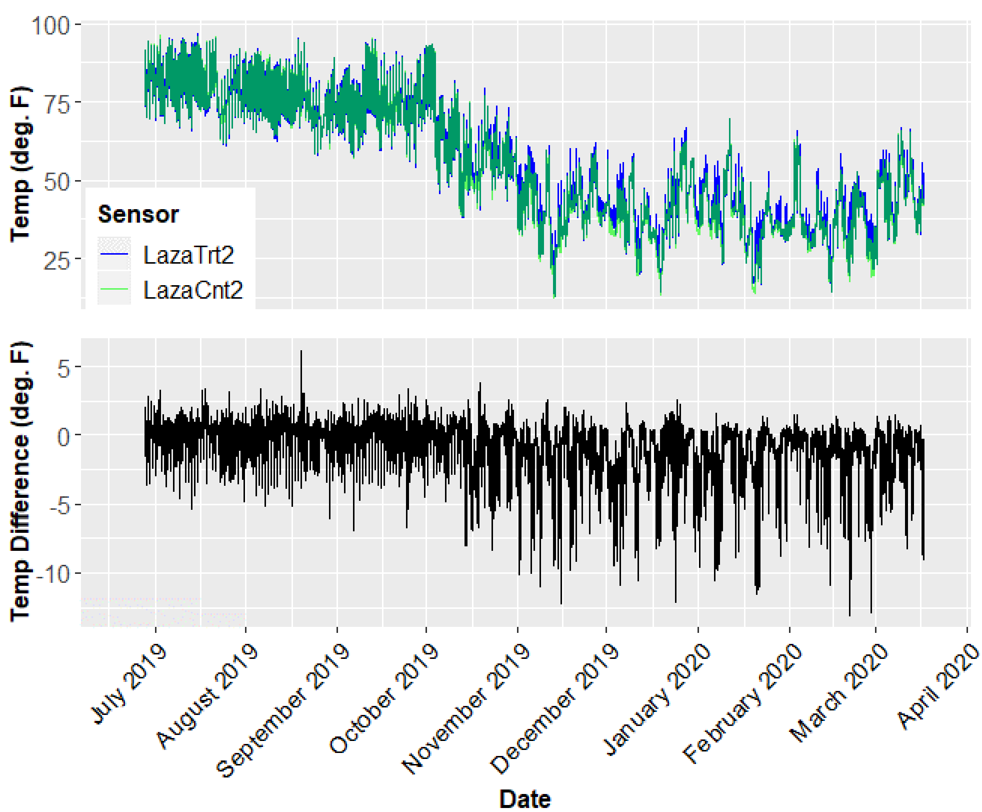
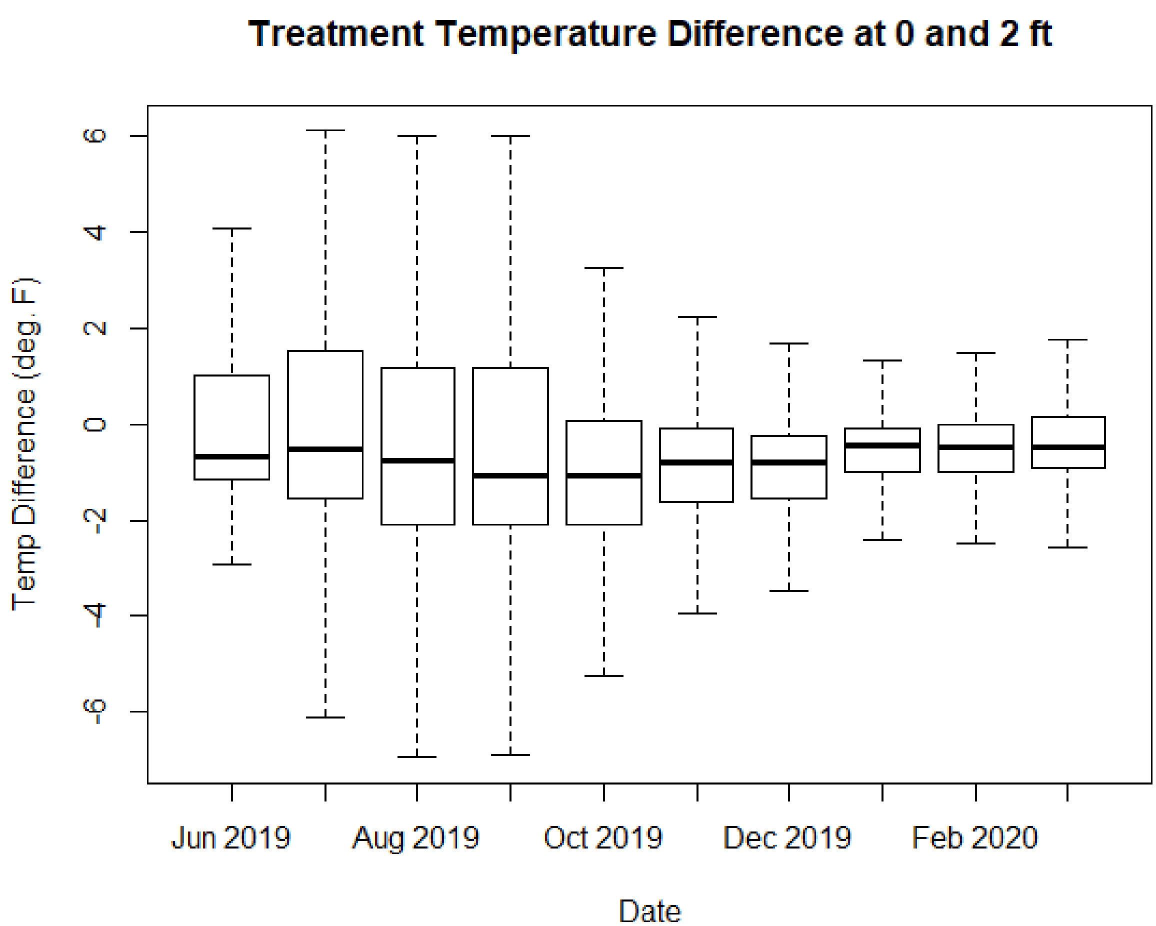


Table 48. Lazarus Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-2.93	-1.16	-0.69	-0.07	1.01	4.09
2019 07	-7.65	-1.54	-0.54	-0.01	1.54	8.19
2019 08	-8.27	-2.09	-0.77	-0.31	1.16	8.04
2019 09	-8.57	-2.08	-1.08	-0.40	1.16	7.95
2019 10	-11.20	-2.08	-1.08	-0.80	0.07	8.72
2019 11	-9.81	-1.63	-0.78	-0.80	-0.08	6.10
2019 12	-10.27	-1.55	-0.78	-1.03	-0.23	5.02
2020 01	-4.78	-1.01	-0.46	-0.50	-0.08	4.41
2020 02	-5.56	-1.00	-0.47	-0.40	0.00	6.18
2020 03	-5.64	-0.93	-0.47	-0.23	0.16	6.64

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



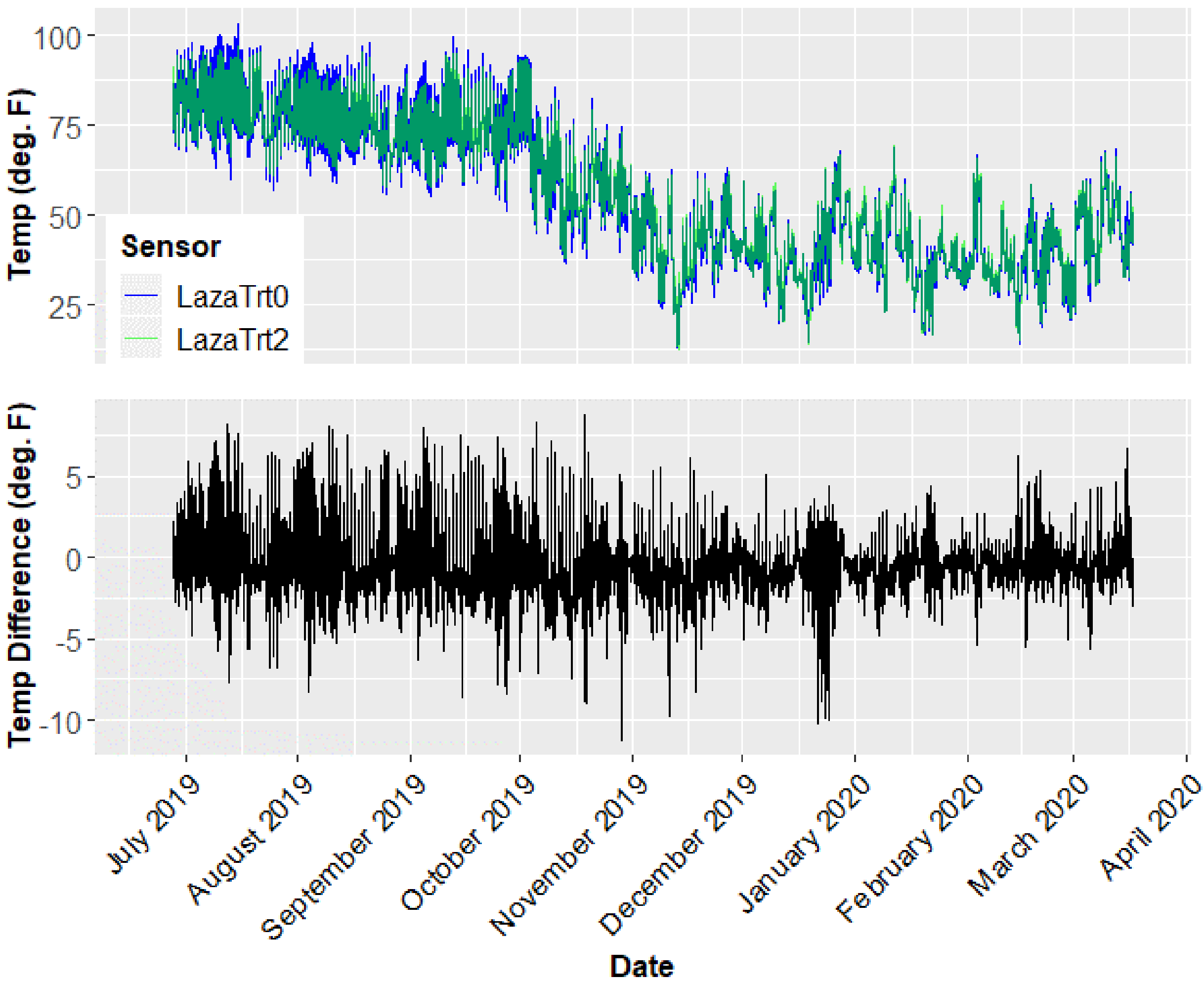
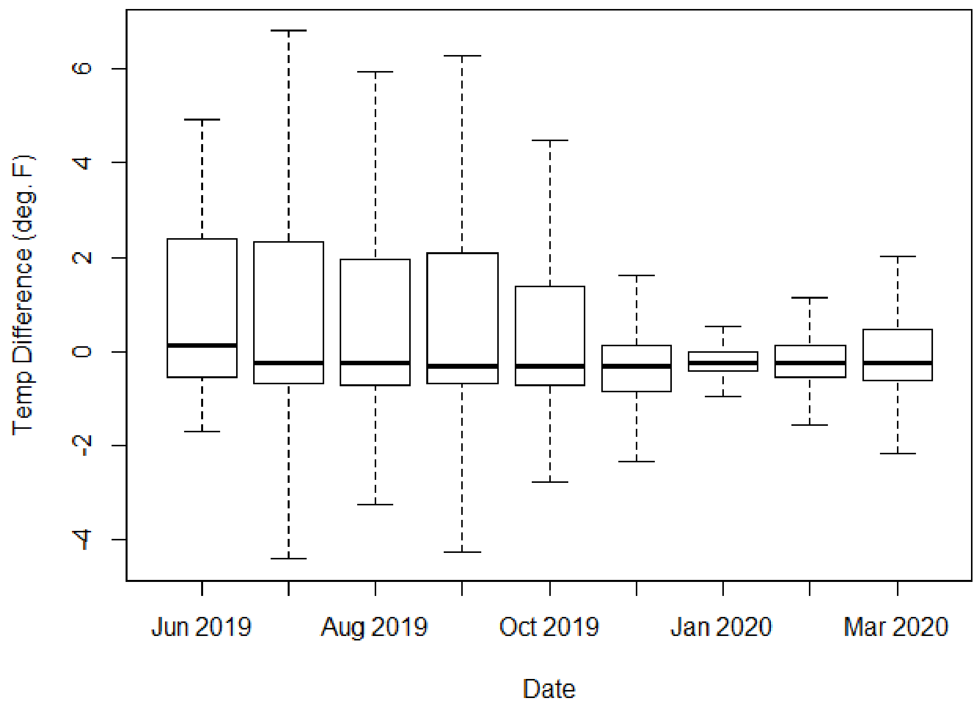


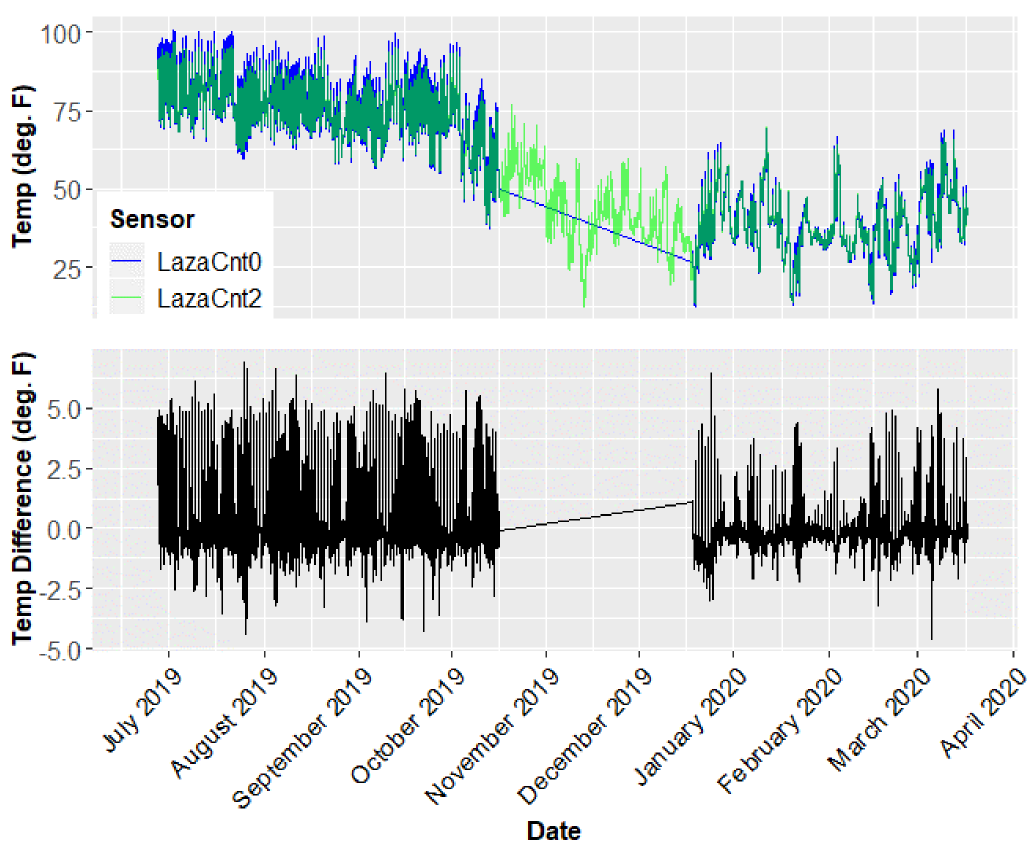
Table 49. Lazarus Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-1.70	-0.54	0.15	0.90	2.40	4.94
2019 07	-4.40	-0.69	-0.23	0.69	2.32	6.88
2019 08	-3.24	-0.70	-0.23	0.57	1.97	6.65
2019 09	-4.25	-0.69	-0.31	0.61	2.09	6.41
2019 10	-2.78	-0.70	-0.31	0.40	1.39	5.72
2019 11	Sensor Malfunction					
2019 12	-3.01	-0.85	-0.31	-0.03	0.15	6.41
2020 01	-2.24	-0.39	-0.23	-0.06	0.00	4.41
2020 02	-3.17	-0.54	-0.23	0.00	0.15	4.94
2020 03	-4.56	-0.61	-0.23	0.18	0.46	5.79

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Control Temperature Difference at 0 and 2 ft



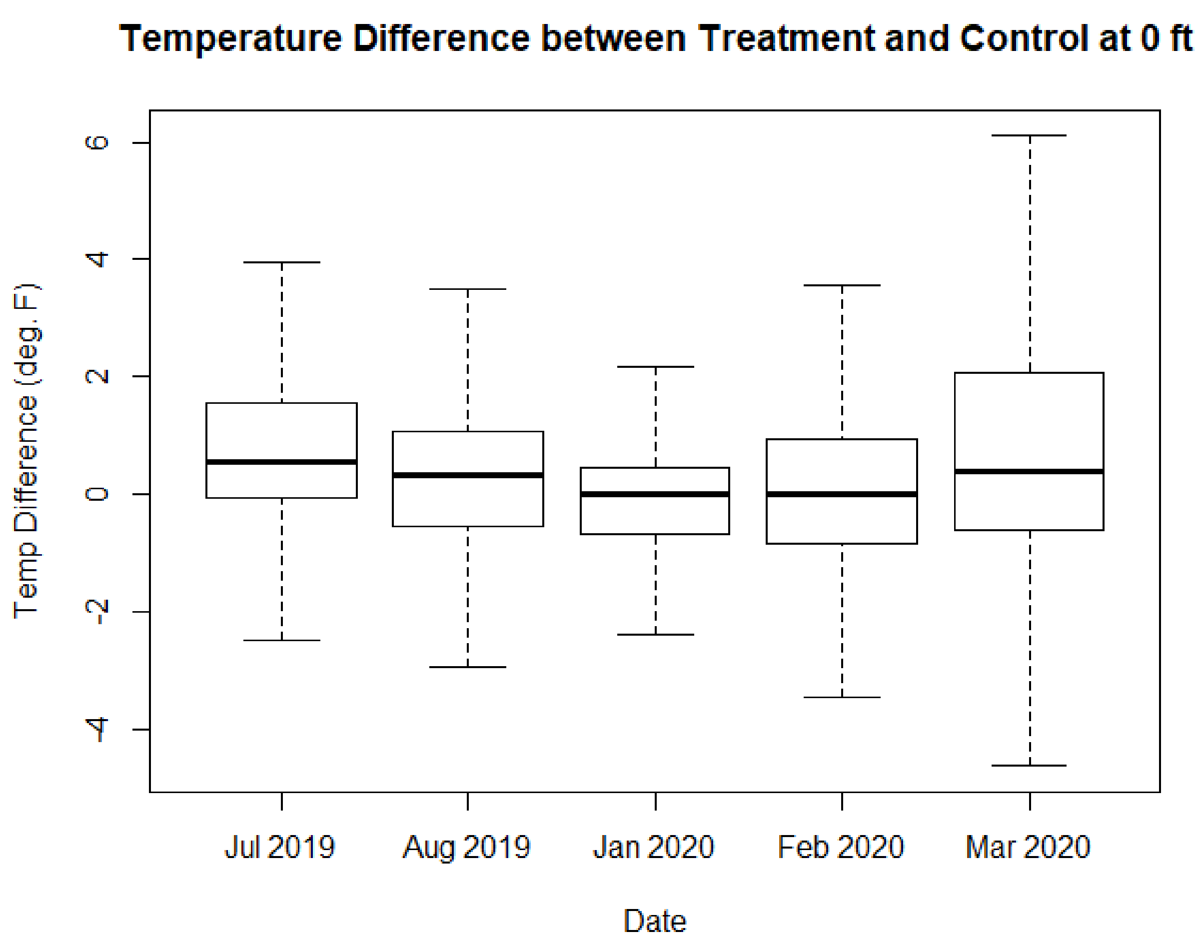


Library

Table 50. Library Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-6.26	-0.08	0.55	0.56	1.54	5.80
2019 08	-6.03	-0.54	0.31	0.12	1.08	4.56
2019 09	--	--	--	--	--	--
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-5.25	-0.69	0.00	0.24	0.46	9.65
2020 02	-5.56	-0.84	0.00	0.64	0.93	13.44
2020 03	-5.33	-0.61	0.39	1.04	2.08	12.36

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



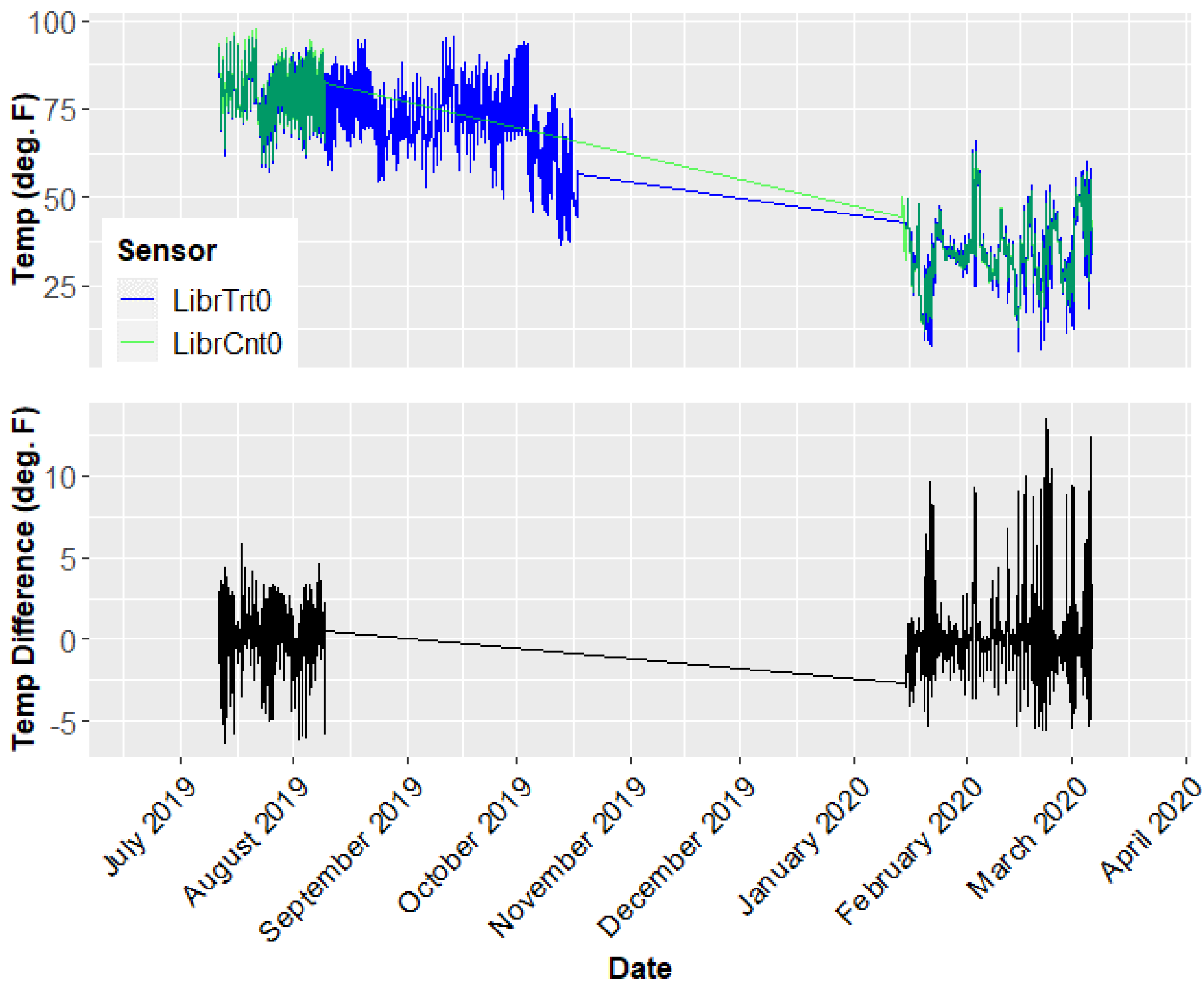
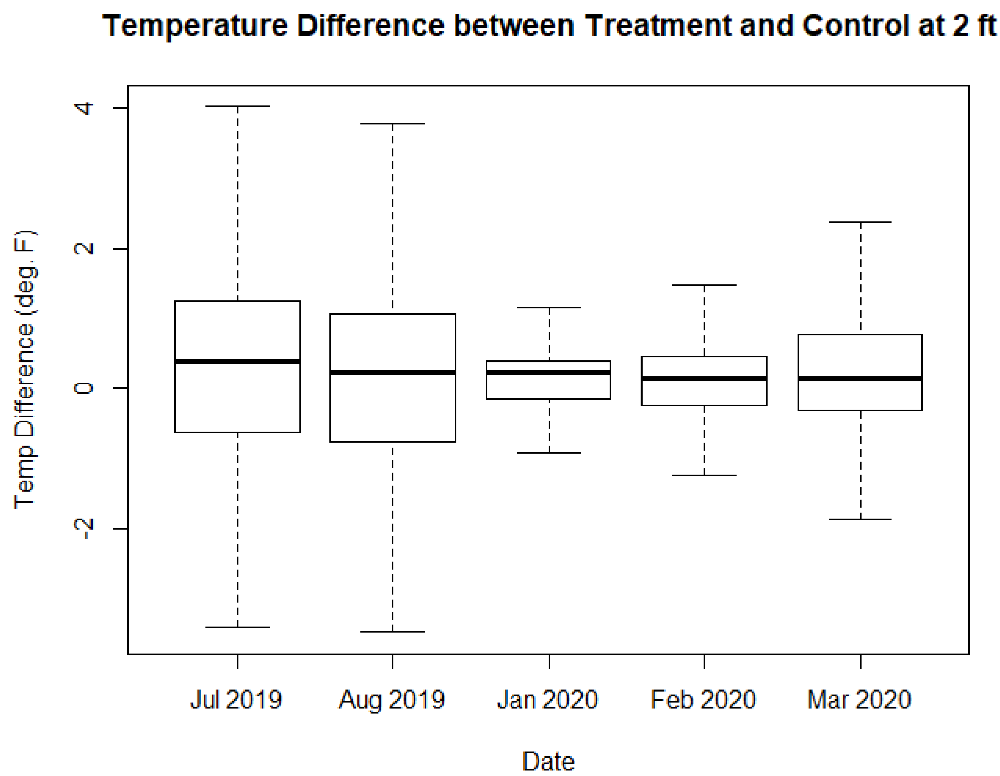


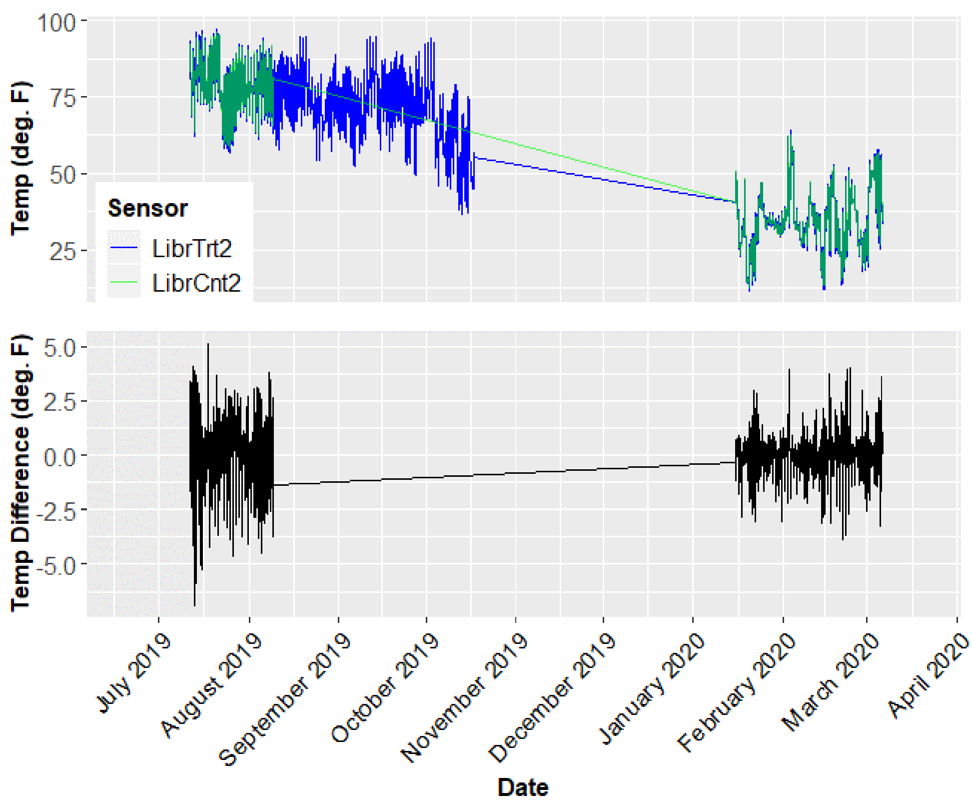
Table 51. Library Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-6.87	-0.62	0.39	0.23	1.24	5.09
2019 08	-4.48	-0.77	0.23	0.11	1.08	3.78
2019 09	--	--	--	--	--	--
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-3.01	-0.15	0.23	0.12	0.39	2.94
2020 02	-3.86	-0.23	0.15	0.15	0.47	4.02
2020 03	-3.25	-0.31	0.15	0.20	0.77	3.56

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Temperature Difference between Treatment and Control at 2 ft
Temp Difference (deg. F)
4
2
0
-2
Jul 2019
Aug 2019
Jan 2020
Feb 2020
Mar 2020
Date

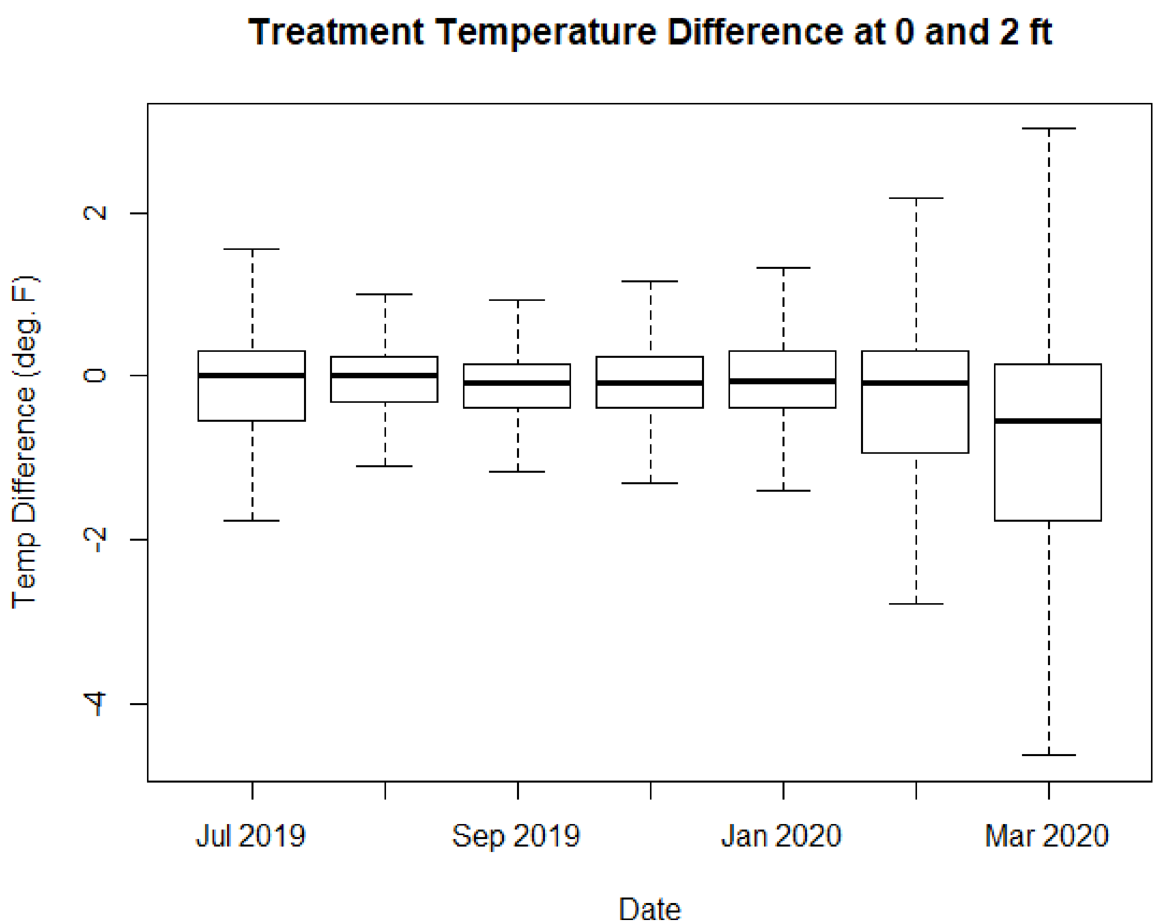


Temp (deg. F)
100
75
50
25
Sensor
LibrTrt2
LibrCnt2
Temp Difference (deg. F)
5.0
2.5
0.0
-2.5
-5.0
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Table 52. Library Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-3.70	-0.54	0.00	-0.14	0.31	3.71
2019 08	-3.32	-0.31	0.00	-0.04	0.23	4.17
2019 09	-3.40	-0.39	-0.08	-0.14	0.15	3.16
2019 10	-2.55	-0.39	-0.08	-0.12	0.23	2.16
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-7.96	-0.39	-0.07	-0.36	0.30	3.94
2020 02	-10.74	-0.93	-0.08	-0.74	0.31	3.86
2020 03	-10.12	-1.77	-0.54	-1.11	0.15	3.63

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



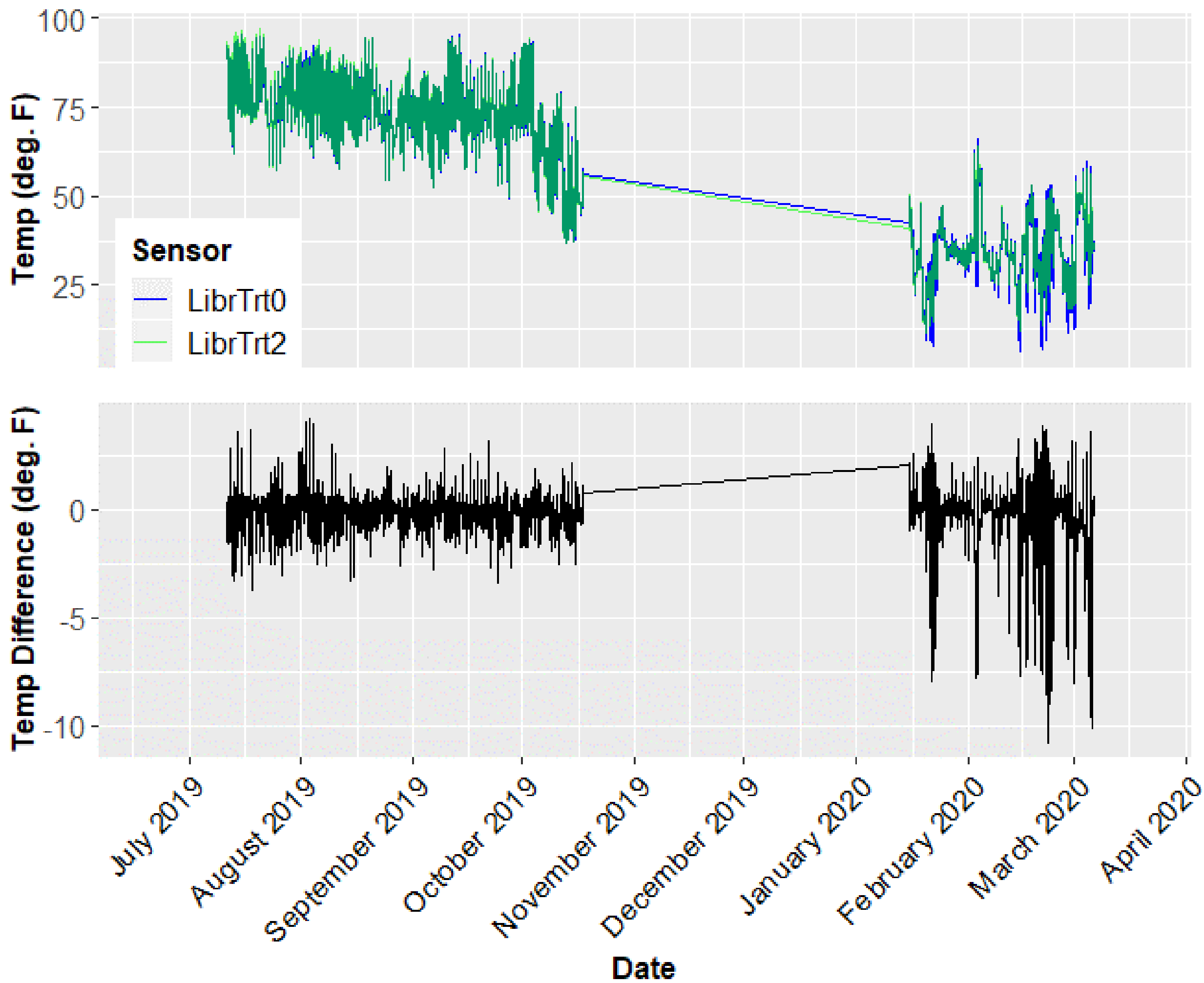
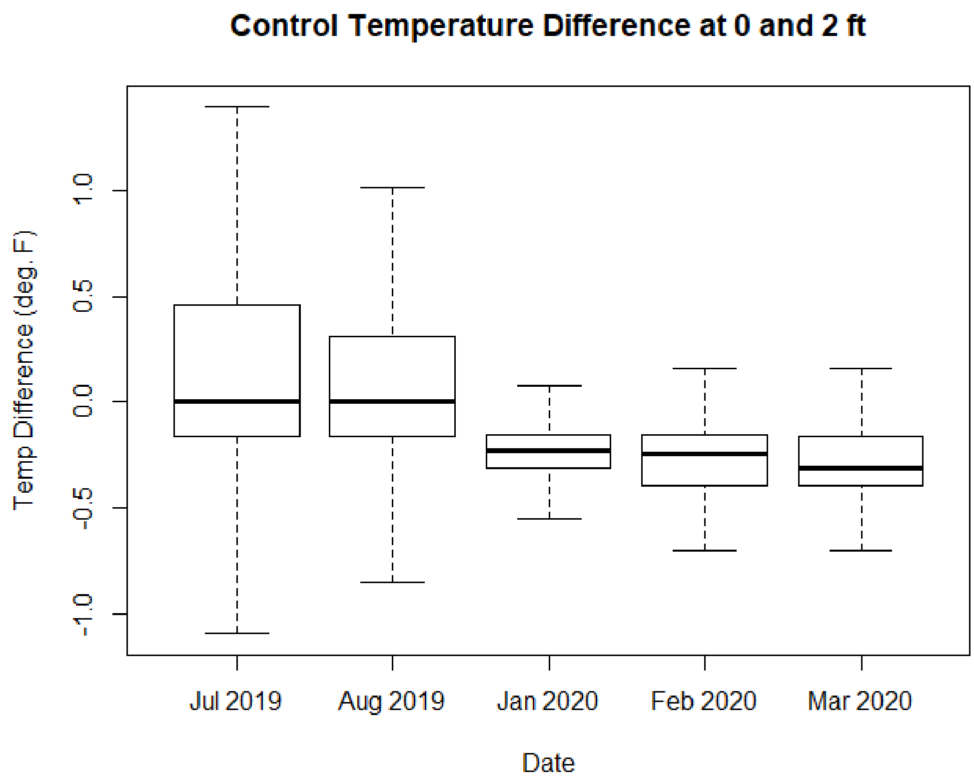


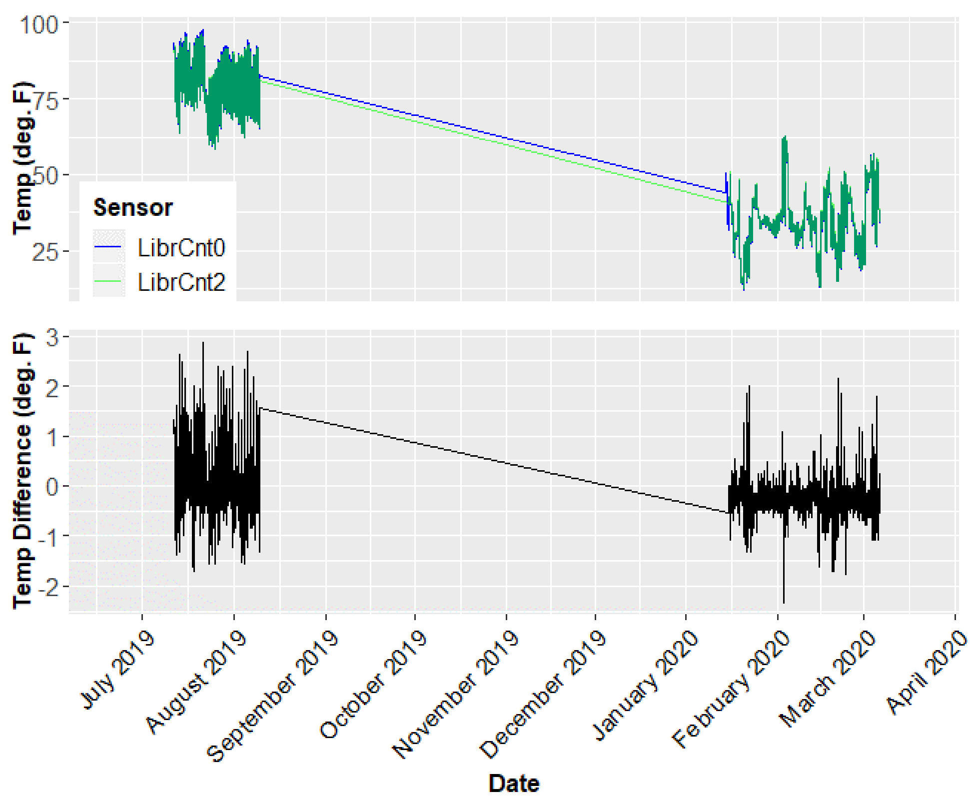
Table 53. Library Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 07	-1.70	-0.16	0.00	0.20	0.46	2.86
2019 08	-1.55	-0.16	0.00	0.13	0.31	2.70
2019 09	--	--	--	--	--	--
2019 10	--	--	--	--	--	--
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-1.32	-0.31	-0.23	-0.24	-0.15	2.01
2020 02	-2.32	-0.39	-0.24	-0.25	-0.15	2.16
2020 03	-1.08	-0.39	-0.31	-0.28	-0.16	1.78

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
1.0
0.5
0.0
-0.5
-1.0
Jul 2019
Aug 2019
Jan 2020
Feb 2020
Mar 2020
Date



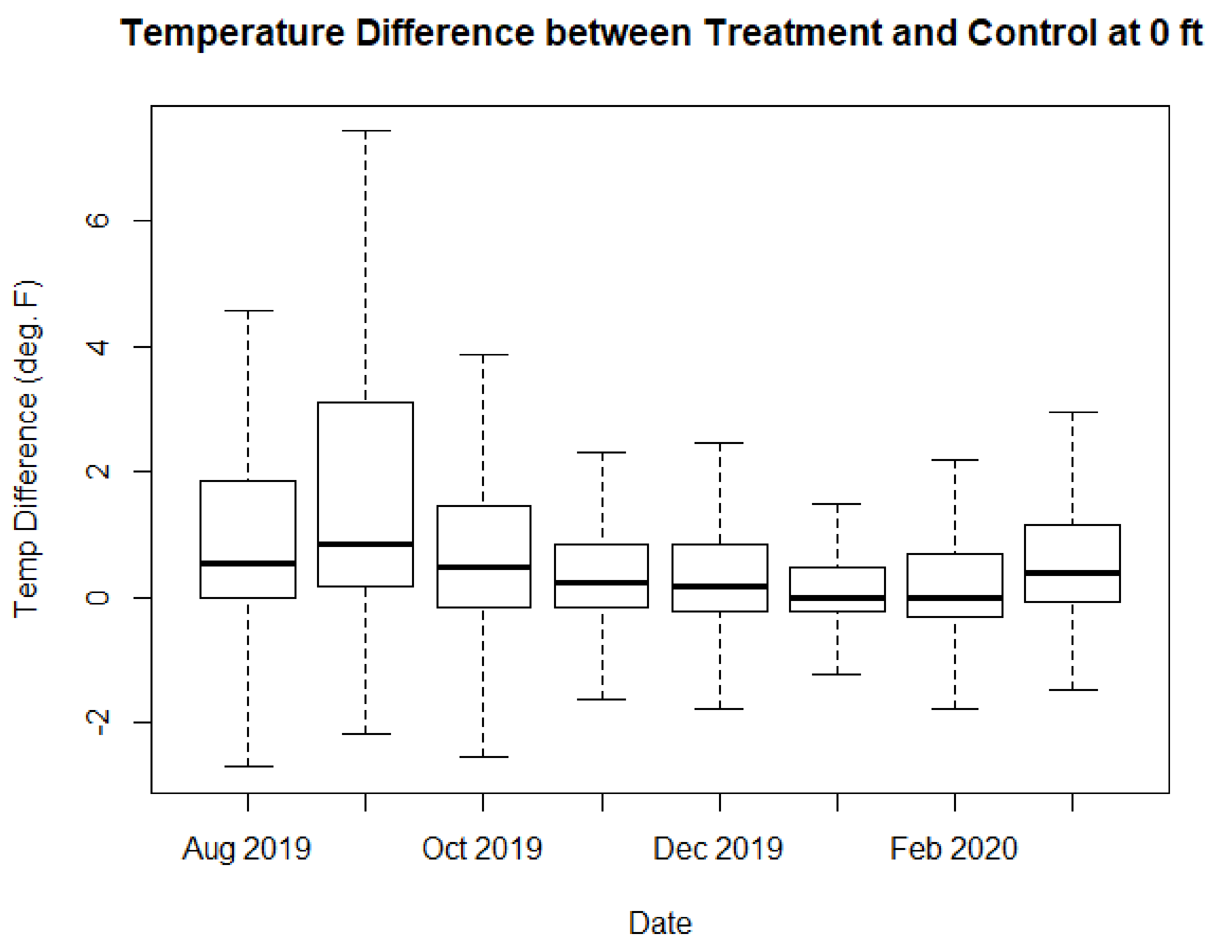
Temp (deg. F)
100
75
50
25
Sensor
LibrCnt0
LibrCnt2
Temp Difference (deg. F)
3
2
1
0
-1
-2
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Main

Table 54. Main Treatment vs Control at 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-4.33	0.00	0.54	1.17	1.85	7.57
2019 09	-2.17	0.16	0.85	1.70	3.09	8.88
2019 10	-3.63	-0.16	0.46	0.96	1.46	8.18
2019 11	-2.08	-0.16	0.23	0.43	0.85	5.86
2019 12	-3.55	-0.23	0.16	0.48	0.85	8.57
2020 01	-1.93	-0.23	0.00	0.22	0.46	5.02
2020 02	-1.77	-0.31	0.00	0.28	0.69	4.87
2020 03	-1.47	-0.07	0.38	0.67	1.16	5.63

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



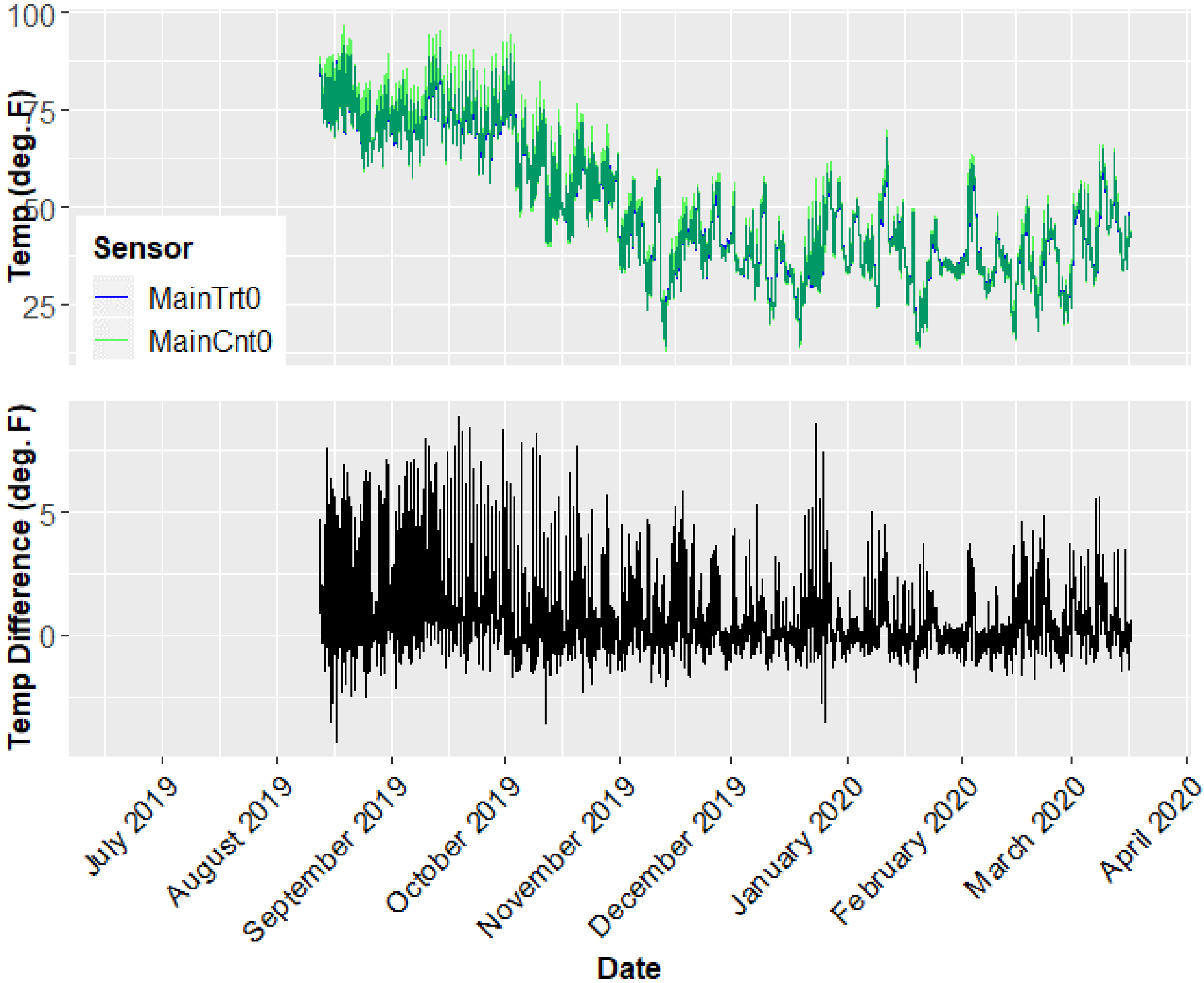
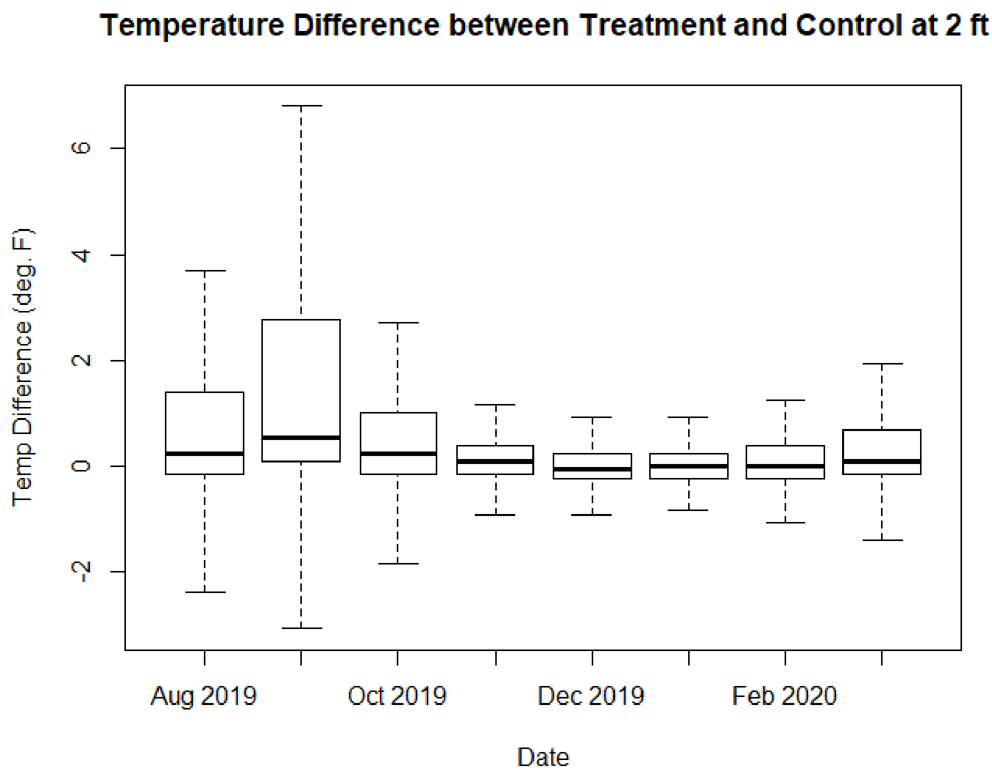


Table 55. Main Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.16	-0.15	0.23	0.96	1.39	7.65
2019 09	-3.08	0.08	0.54	1.55	2.78	8.50
2019 10	-2.63	-0.15	0.23	0.89	1.01	7.88
2019 11	-2.40	-0.15	0.08	0.41	0.39	6.48
2019 12	-3.94	-0.23	-0.07	0.22	0.24	7.96
2020 01	-1.39	-0.23	0.00	0.18	0.23	6.33
2020 02	-2.62	-0.23	0.00	0.28	0.38	6.03
2020 03	-1.70	-0.15	0.08	0.53	0.69	8.19

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.


Temperature Difference between Treatment and Control at 2 ft
Temp Difference (deg. F)
-2
0
2
4
6
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date

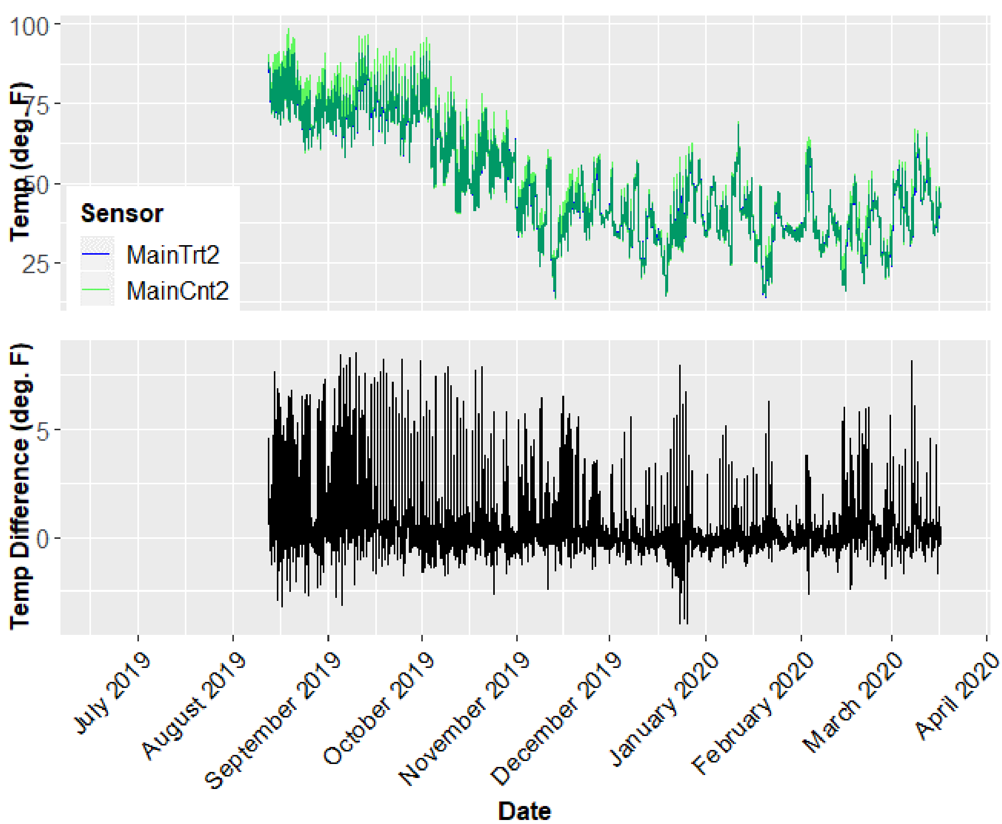
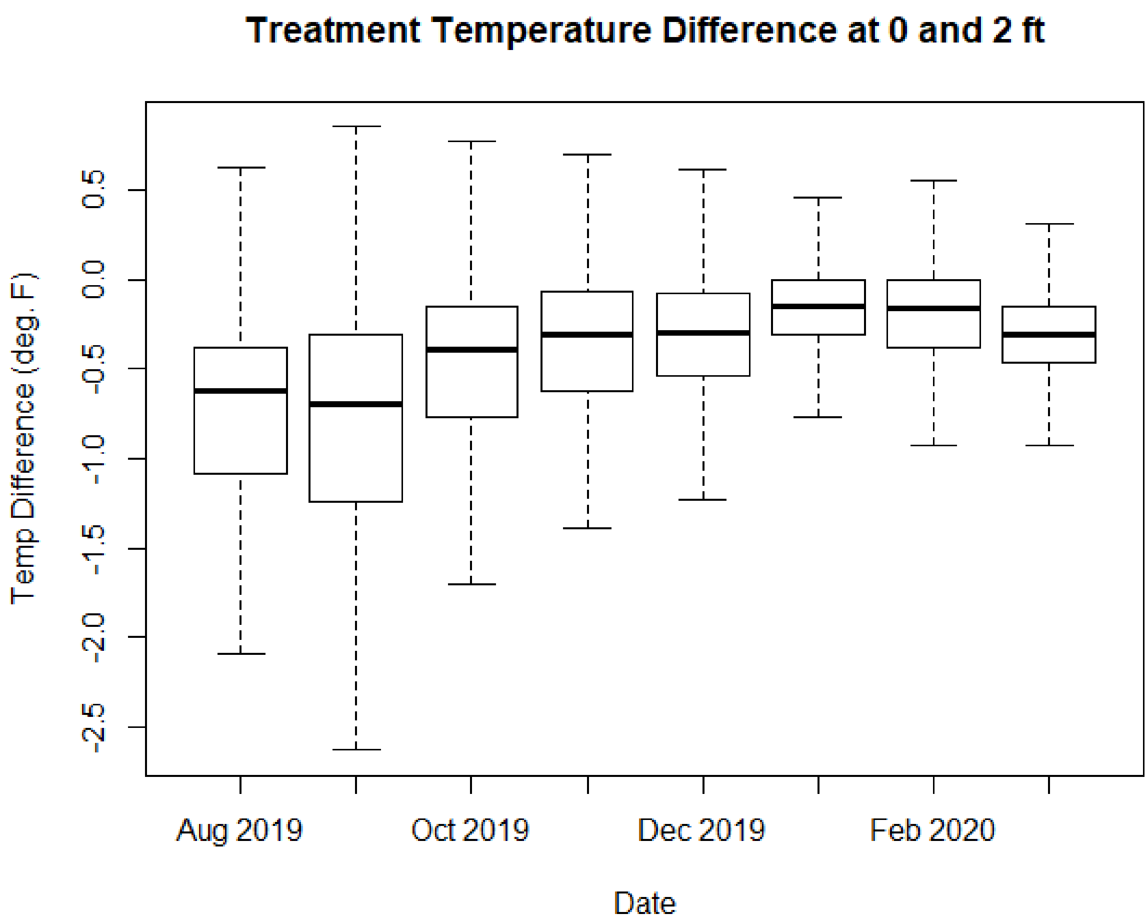

Temp (deg. F)
100
75
50
25
Sensor
MainTrt2
MainCnt2
Temp Difference (deg. F)
5
0
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Table 56. Main Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.25	-1.08	-0.62	-0.74	-0.38	1.78
2019 09	-3.55	-1.24	-0.70	-0.82	-0.31	0.85
2019 10	-3.02	-0.77	-0.39	-0.50	-0.15	1.93
2019 11	-2.94	-0.62	-0.31	-0.32	-0.07	1.16
2019 12	-3.25	-0.54	-0.30	-0.35	-0.08	1.24
2020 01	-1.70	-0.31	-0.15	-0.18	0.00	0.85
2020 02	-1.70	-0.38	-0.16	-0.19	0.00	0.85
2020 03	-1.93	-0.47	-0.31	-0.31	-0.15	1.31

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



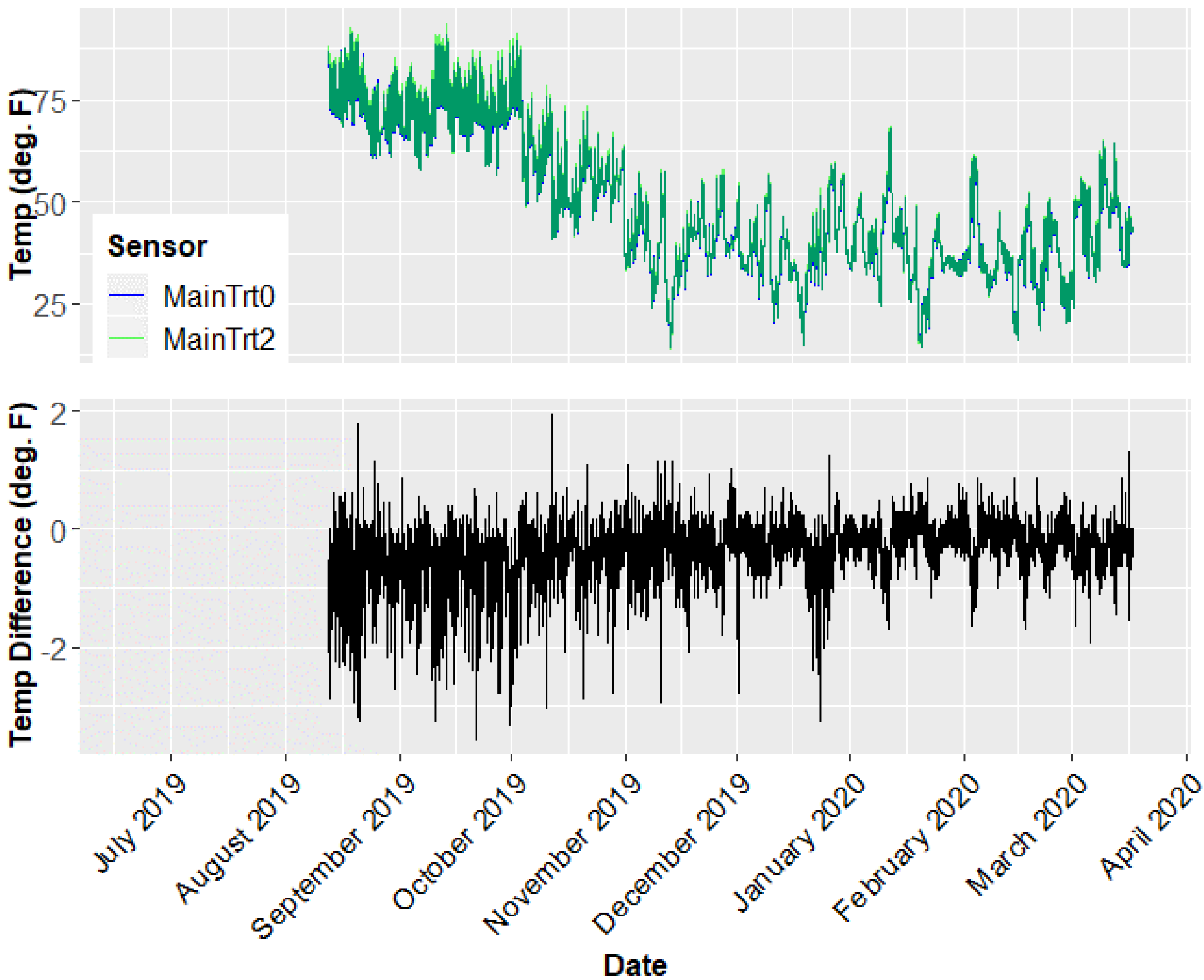
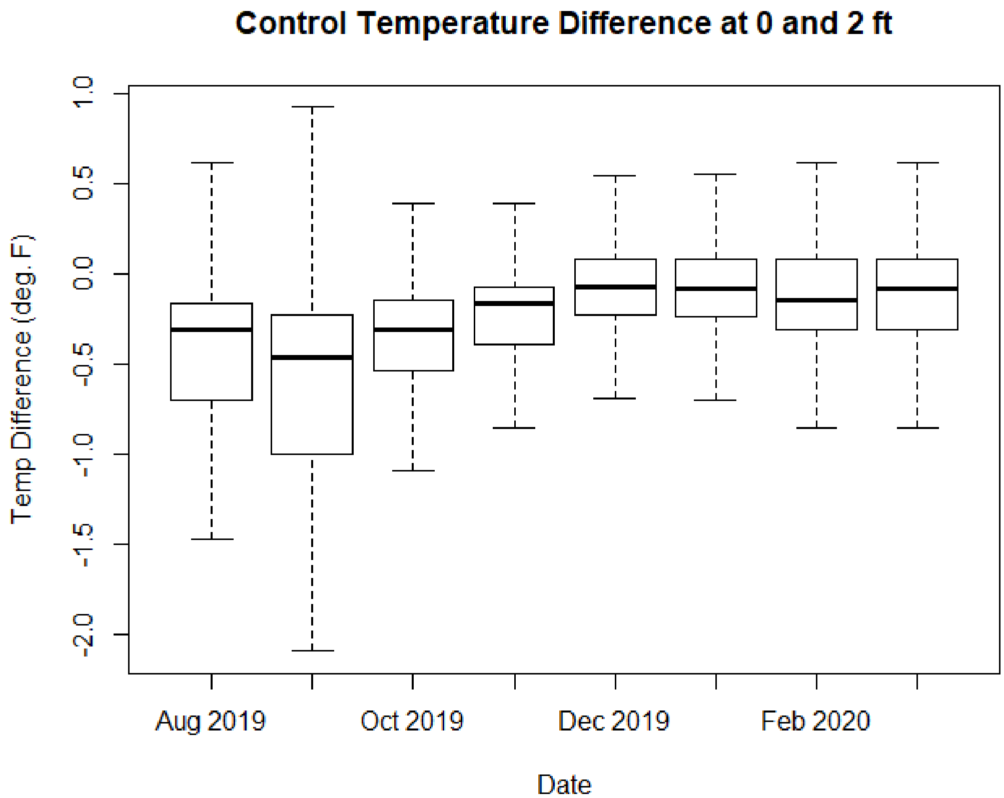


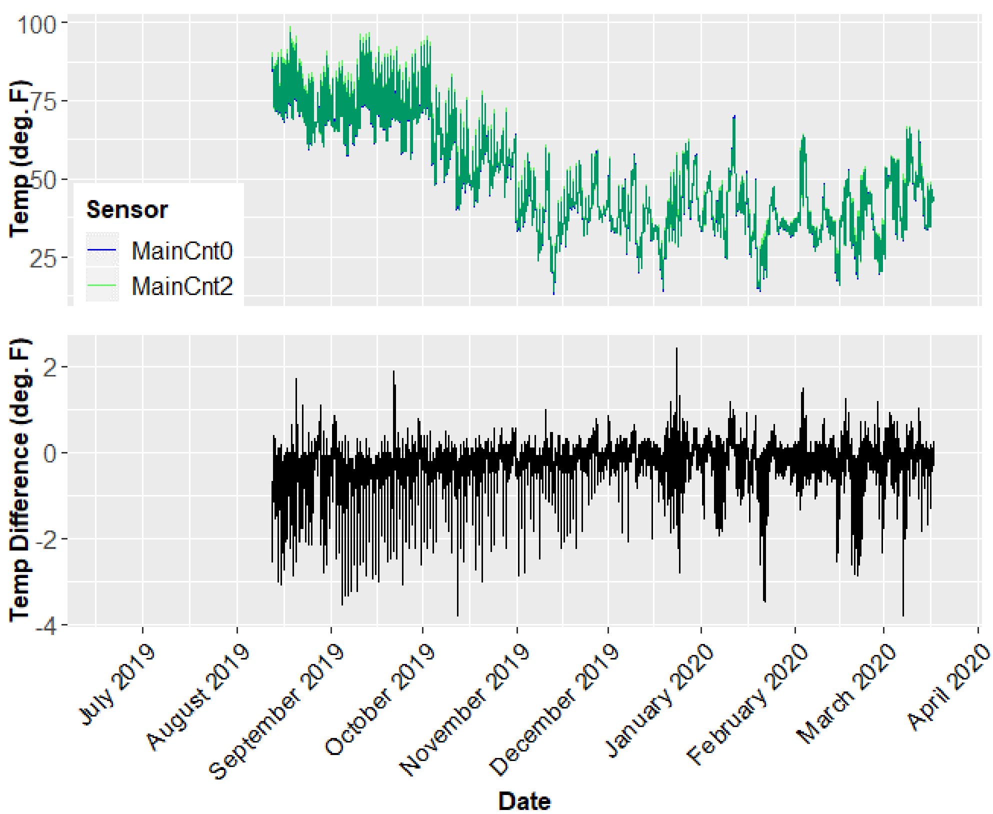
Table 57. Main Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.09	-0.70	-0.31	-0.53	-0.16	1.70
2019 09	-3.55	-1.00	-0.46	-0.67	-0.23	1.86
2019 10	-3.78	-0.54	-0.31	-0.44	-0.15	0.54
2019 11	-2.86	-0.39	-0.16	-0.30	-0.07	1.00
2019 12	-2.78	-0.23	-0.07	-0.09	0.08	2.40
2020 01	-3.48	-0.24	-0.08	-0.14	0.08	1.16
2020 02	-2.86	-0.31	-0.15	-0.19	0.08	1.47
2020 03	-3.78	-0.31	-0.08	-0.17	0.08	1.01

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Aug 2019
Oct 2019
Dec 2019
Feb 2020
Date



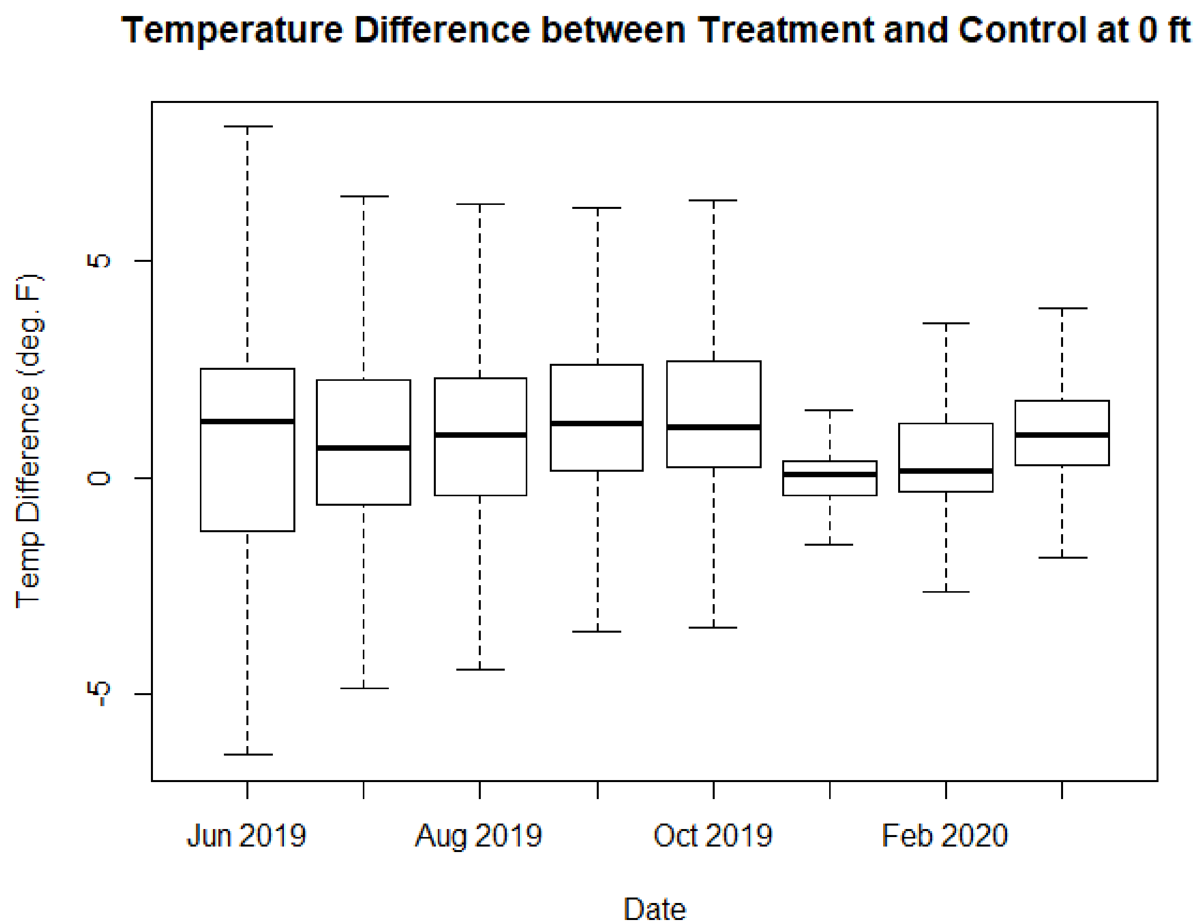
Temp (deg. F)
100
75
50
25
Sensor
MainCnt0
MainCnt2
Temp Difference (deg. F)
2
0
-2
-4
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Star

Table 58. Star Treatment vs Control 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-6.41	-1.24	1.32	0.71	2.54	10.88
2019 07	-9.57	-0.62	0.70	0.53	2.24	7.80
2019 08	-10.12	-0.39	1.00	0.72	2.32	8.19
2019 09	-9.11	0.15	1.24	1.03	2.62	8.34
2019 10	-8.11	0.23	1.16	1.29	2.70	7.88
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-4.17	-0.39	0.07	0.00	0.39	4.94
2020 02	-5.49	-0.31	0.16	0.62	1.24	9.96
2020 03	-4.33	0.31	1.01	0.96	1.78	6.95

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



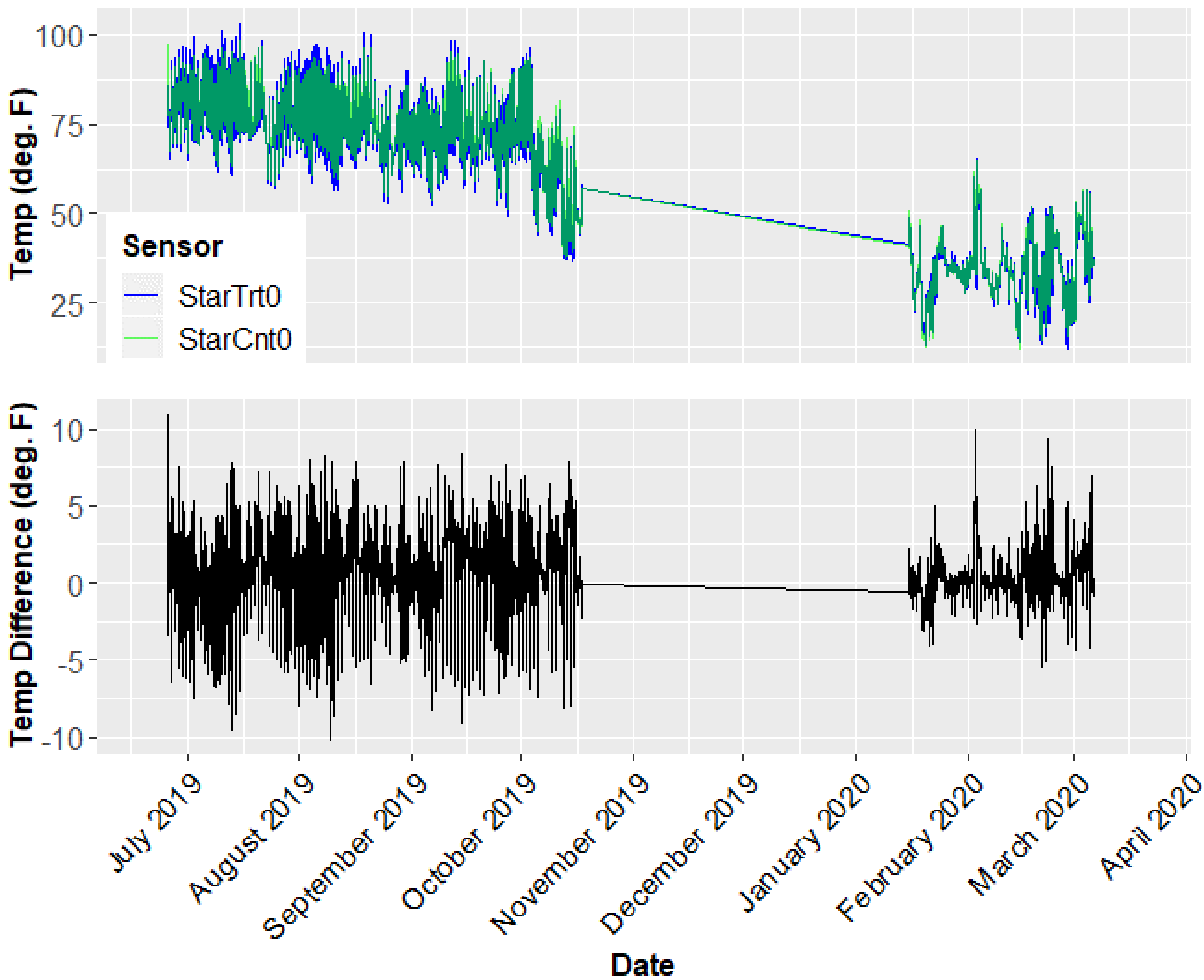
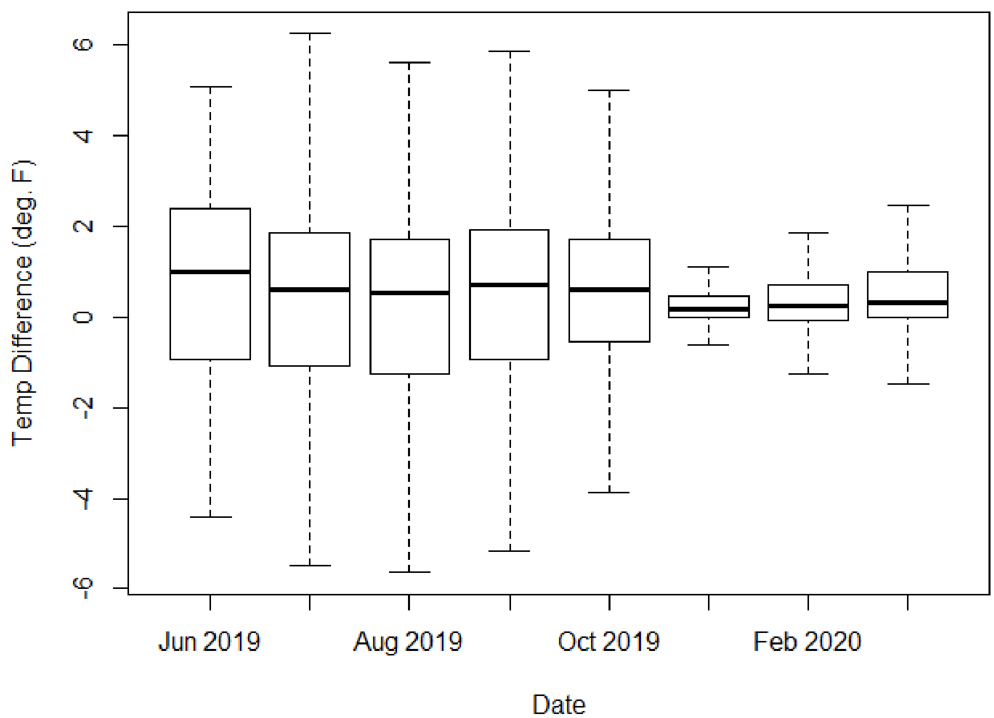


Table 59. Star Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-4.41	-0.93	1.00	0.68	2.39	5.10
2019 07	-7.64	-1.08	0.62	0.36	1.86	6.64
2019 08	-8.96	-1.24	0.54	0.16	1.70	5.64
2019 09	-7.41	-0.92	0.70	0.48	1.93	5.87
2019 10	-6.95	-0.54	0.61	0.41	1.70	5.79
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-2.00	0.00	0.16	0.25	0.46	3.63
2020 02	-3.16	-0.08	0.23	0.52	0.70	6.64
2020 03	-1.93	0.00	0.31	0.55	1.00	5.63

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



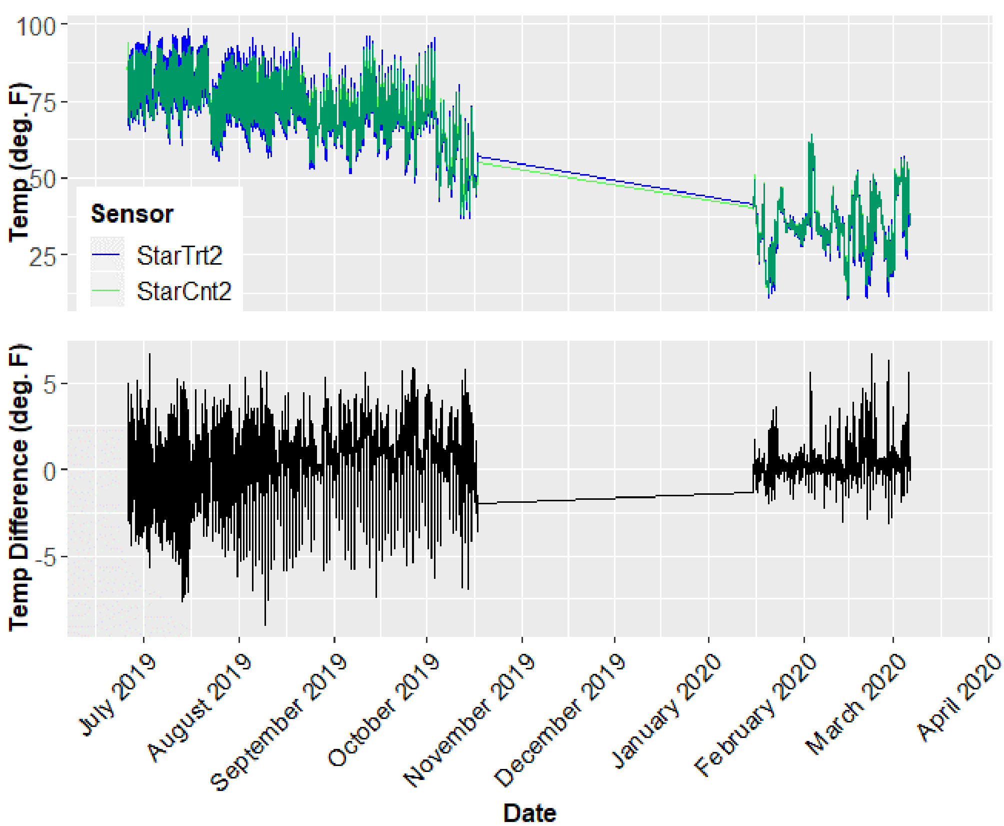
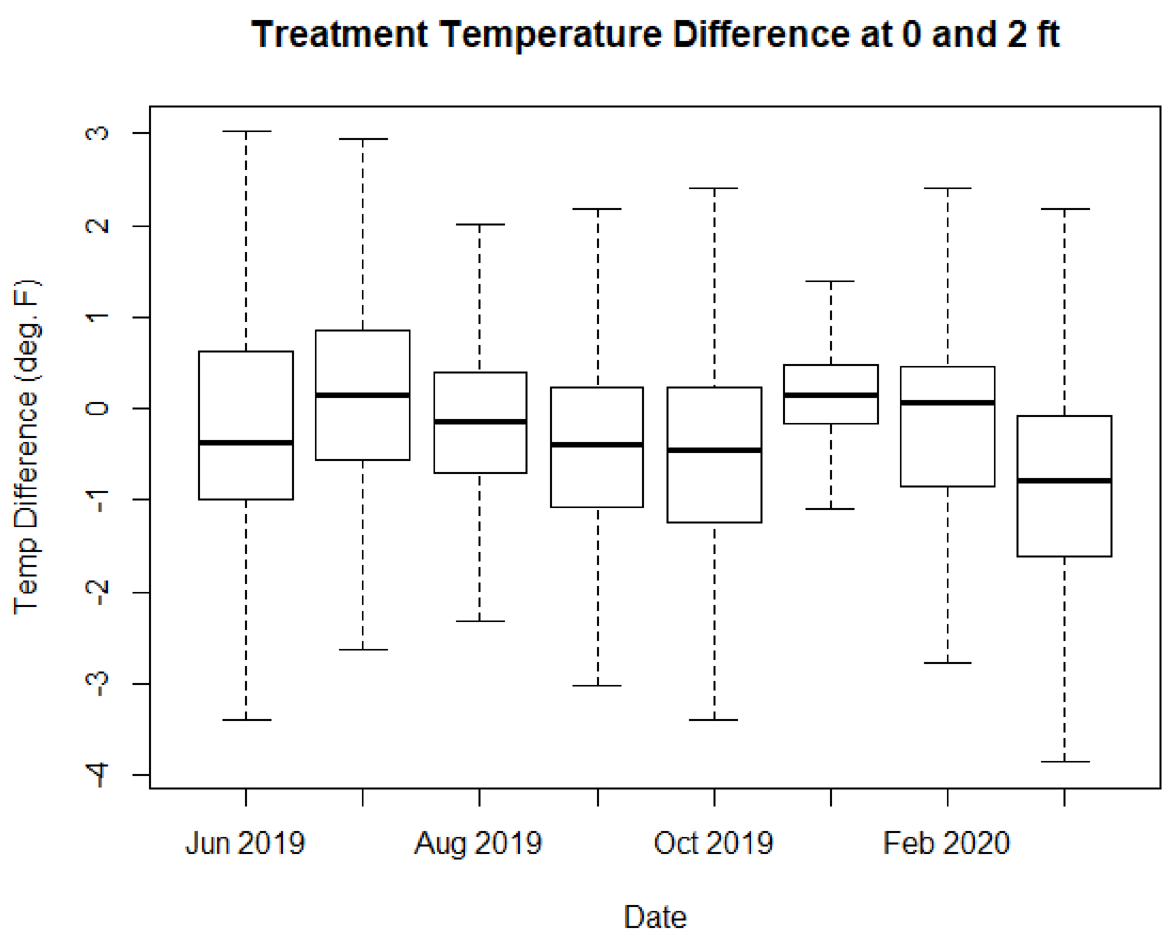


Table 60. Star Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-3.55	-1.00	-0.38	-0.09	0.62	3.55
2019 07	-4.71	-0.55	0.15	0.32	0.85	5.95
2019 08	-3.79	-0.70	-0.15	0.12	0.39	6.49
2019 09	-4.33	-1.08	-0.39	-0.33	0.23	5.33
2019 10	-4.41	-1.24	-0.46	-0.54	0.23	3.48
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-2.71	-0.16	0.15	0.19	0.47	3.86
2020 02	-6.03	-0.85	0.07	-0.23	0.46	4.94
2020 03	-4.33	-1.62	-0.78	-0.64	-0.08	4.56

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



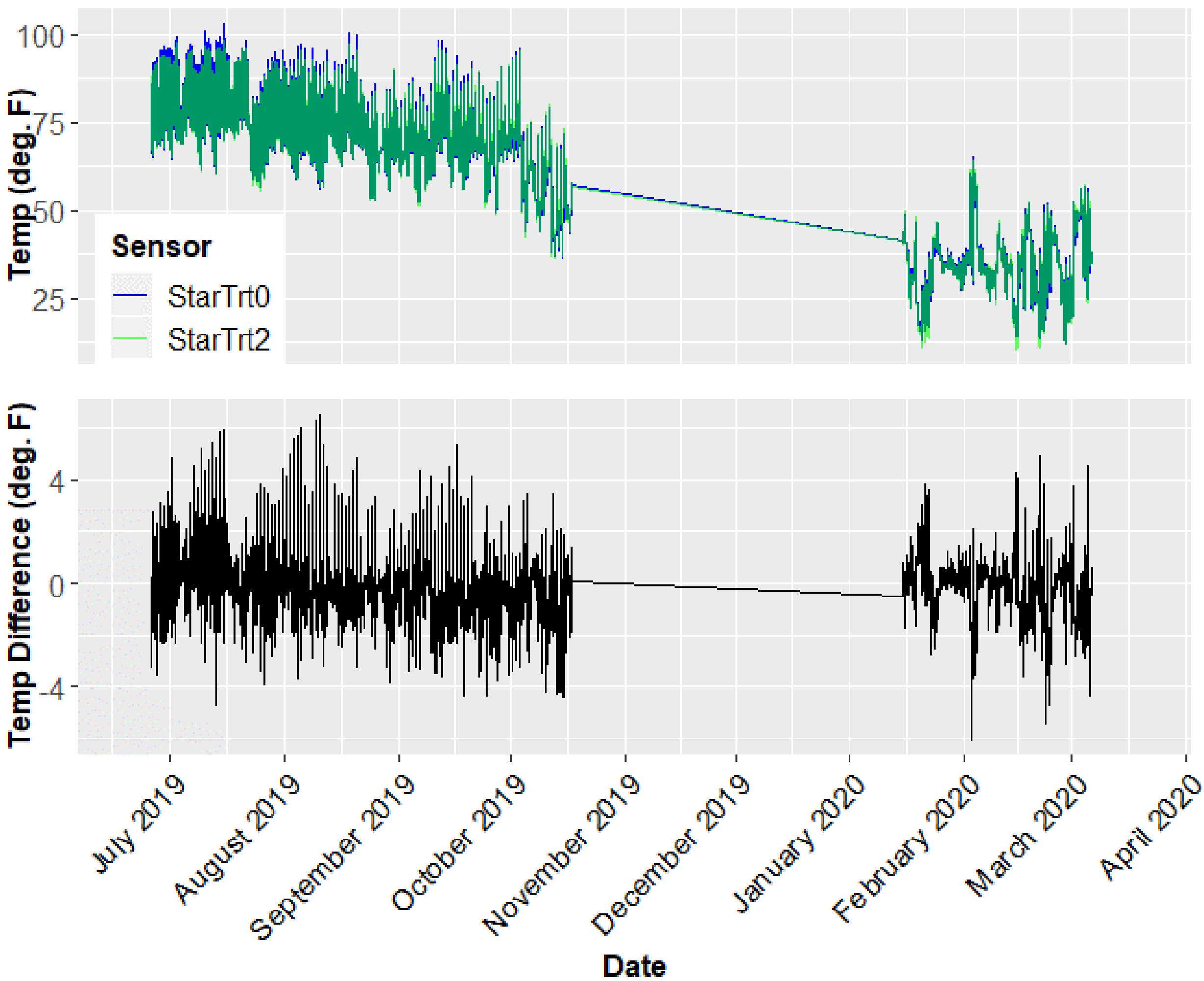
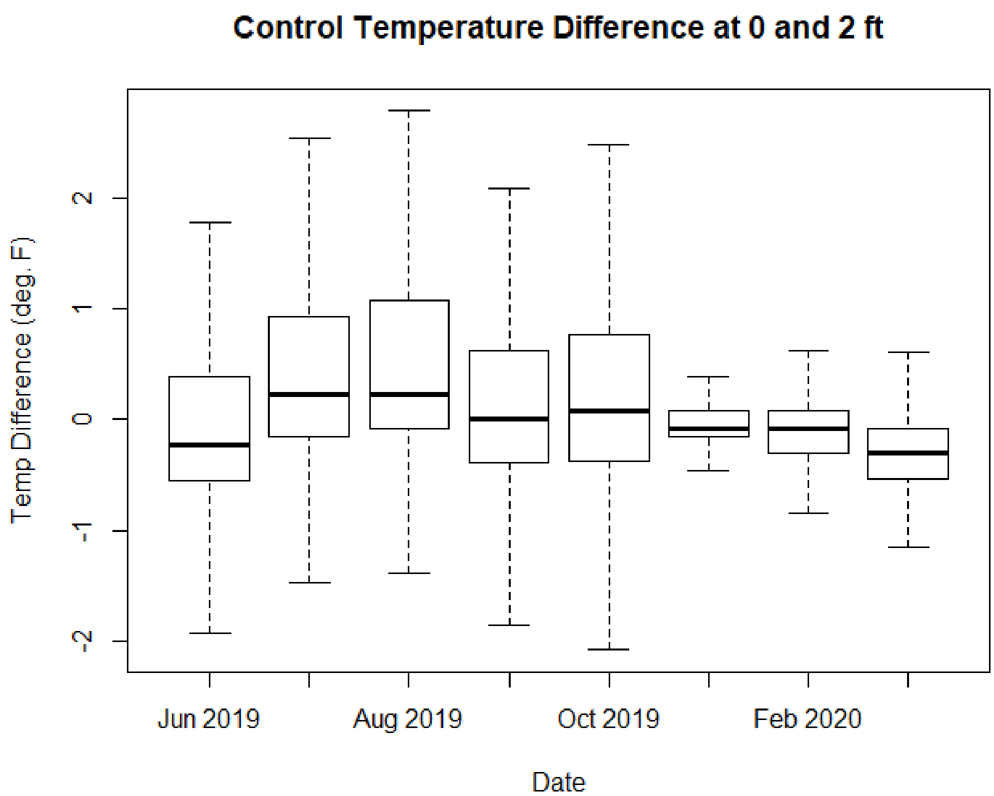


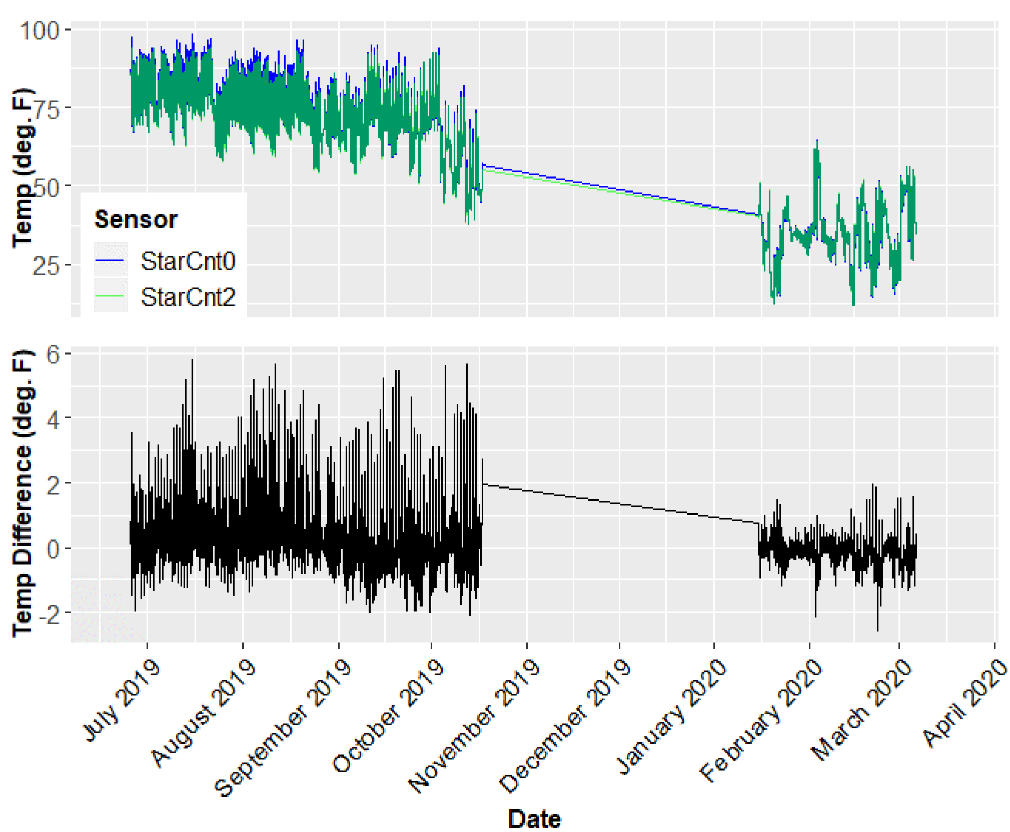
Table 61. Star Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 06	-1.93	-0.55	-0.23	-0.05	0.39	3.56
2019 07	-1.47	-0.16	0.23	0.49	0.92	5.79
2019 08	-1.39	-0.08	0.23	0.68	1.08	5.64
2019 09	-2.01	-0.39	0.00	0.22	0.62	5.49
2019 10	-2.08	-0.38	0.08	0.34	0.77	5.64
2019 11	--	--	--	--	--	--
2019 12	--	--	--	--	--	--
2020 01	-1.16	-0.16	-0.08	-0.06	0.08	1.47
2020 02	-2.55	-0.31	-0.08	-0.13	0.08	1.93
2020 03	-1.32	-0.54	-0.31	-0.23	-0.08	1.55

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
2
1
0
-1
-2
Jun 2019
Aug 2019
Oct 2019
Feb 2020
Date



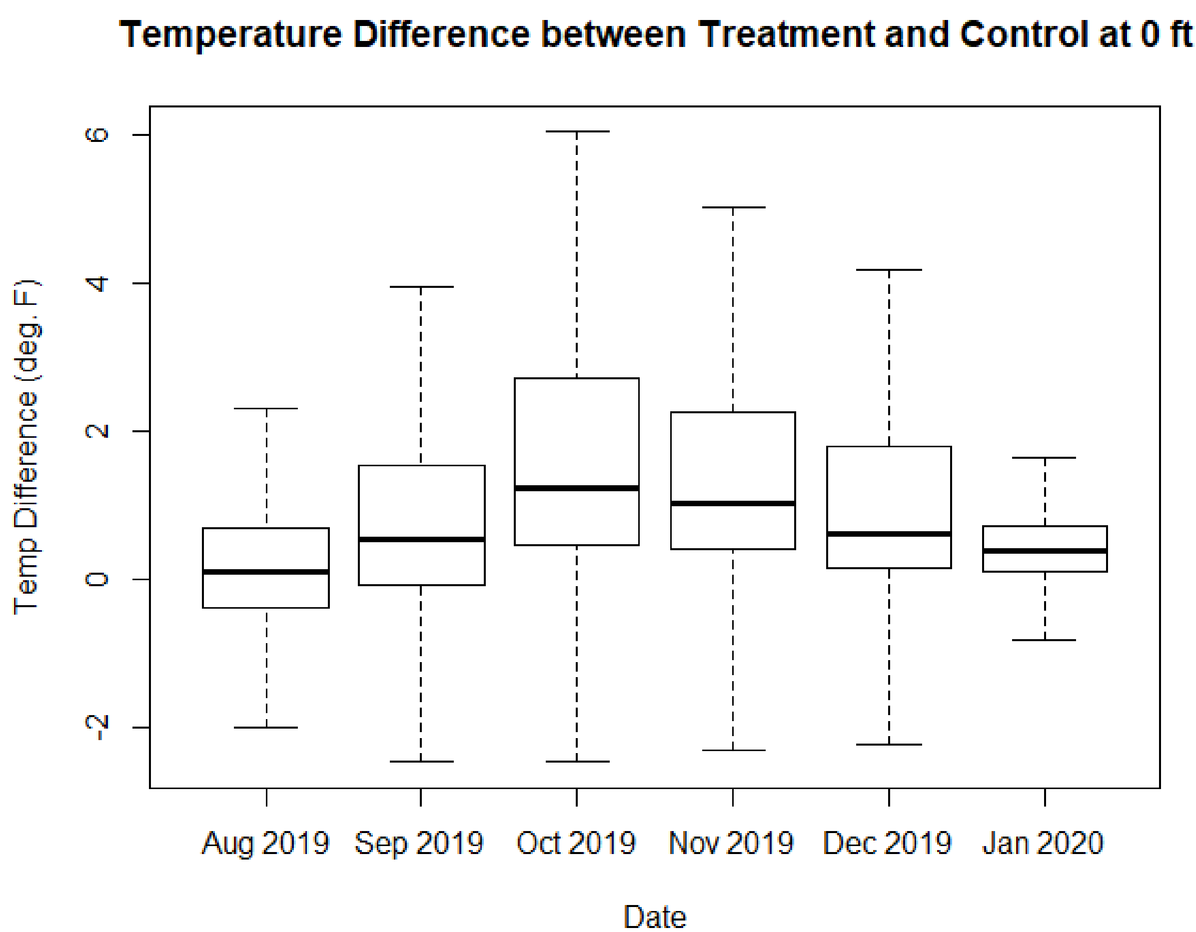
Temp (deg. F)
100
75
50
25
Sensor
StarCnt0
StarCnt2
Temp Difference (deg. F)
6
4
2
0
-2
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Whetstone

Table 62. Whetstone Treatment vs Control 0 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-7.02	-0.39	0.08	0.15	0.69	5.02
2019 09	-3.16	-0.08	0.54	0.91	1.54	10.34
2019 10	-2.48	0.46	1.23	1.75	2.70	14.06
2019 11	-4.48	0.39	1.01	1.49	2.24	12.20
2019 12	-4.40	0.15	0.61	1.33	1.78	12.97
2020 01	-2.16	0.08	0.38	0.61	0.70	11.97

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



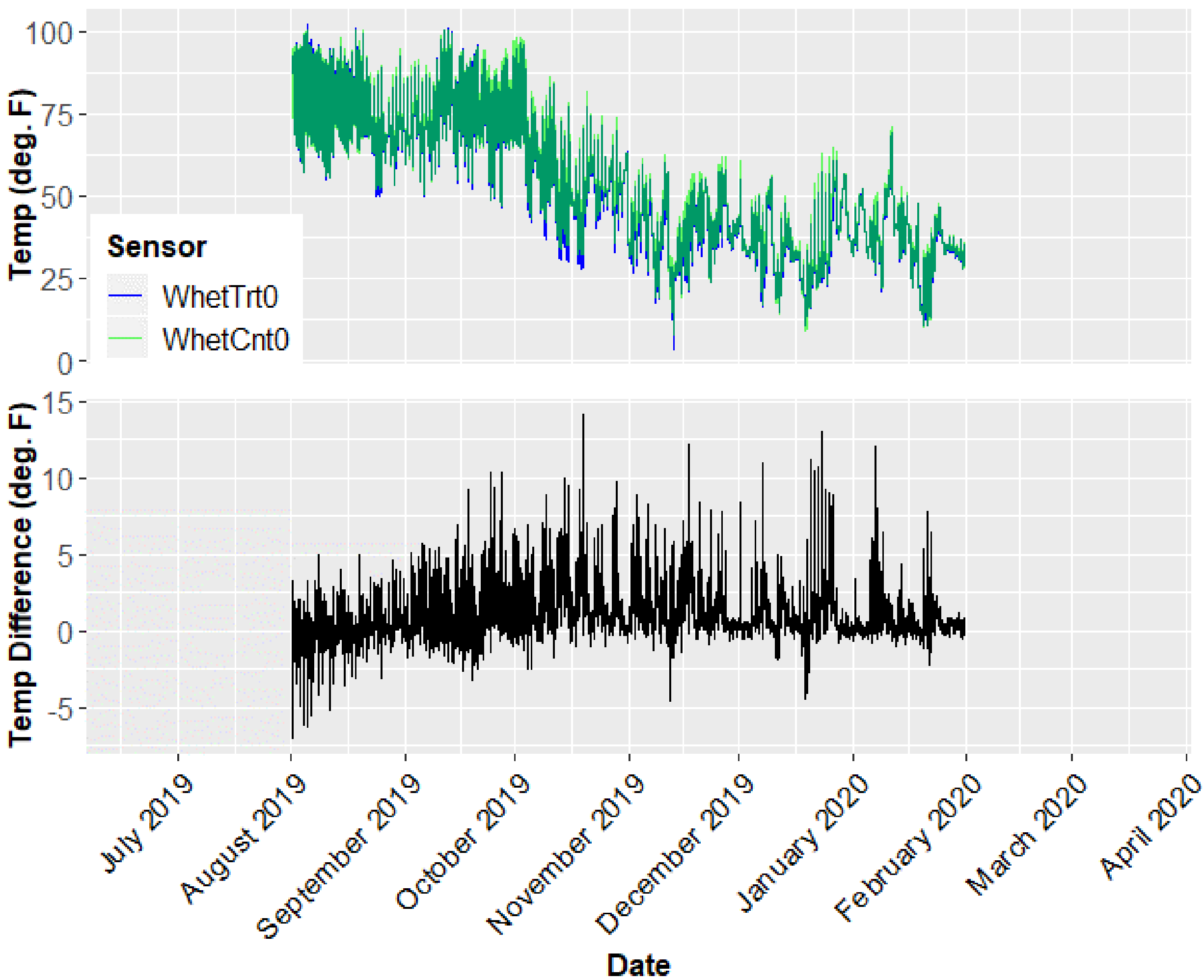
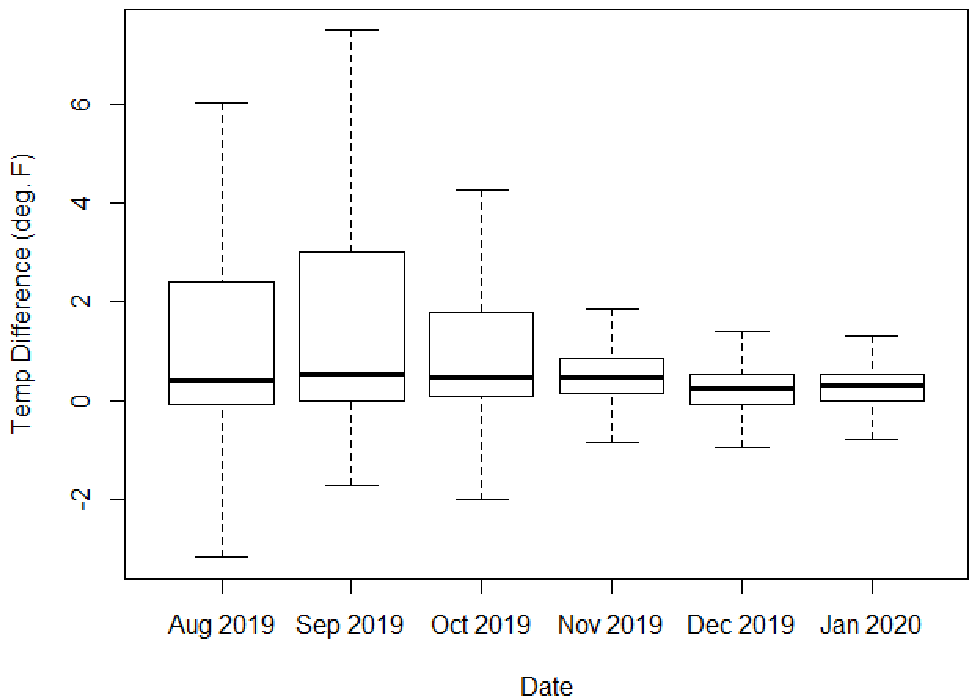


Table 63. Whetstone Treatment vs Control at 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.17	-0.08	0.39	1.22	2.39	7.80
2019 09	-1.70	0.00	0.54	1.52	3.01	7.57
2019 10	-2.01	0.08	0.47	1.11	1.77	7.26
2019 11	-1.09	0.15	0.46	0.82	0.85	8.34
2019 12	-1.39	-0.07	0.24	0.56	0.54	8.49
2020 01	-1.01	0.00	0.30	0.48	0.54	7.64

Note: Positive values indicate the control site temperature measured was greater than the treatment site. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.

Temperature Difference between Treatment and Control at 2 ft



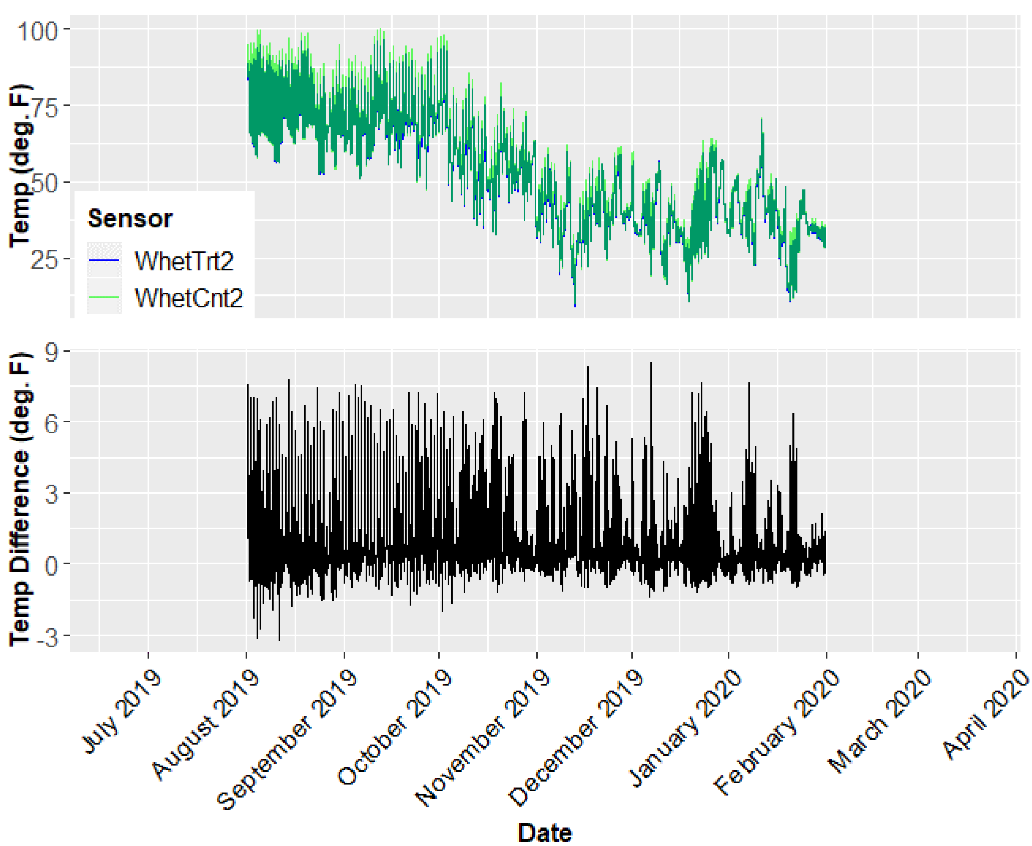
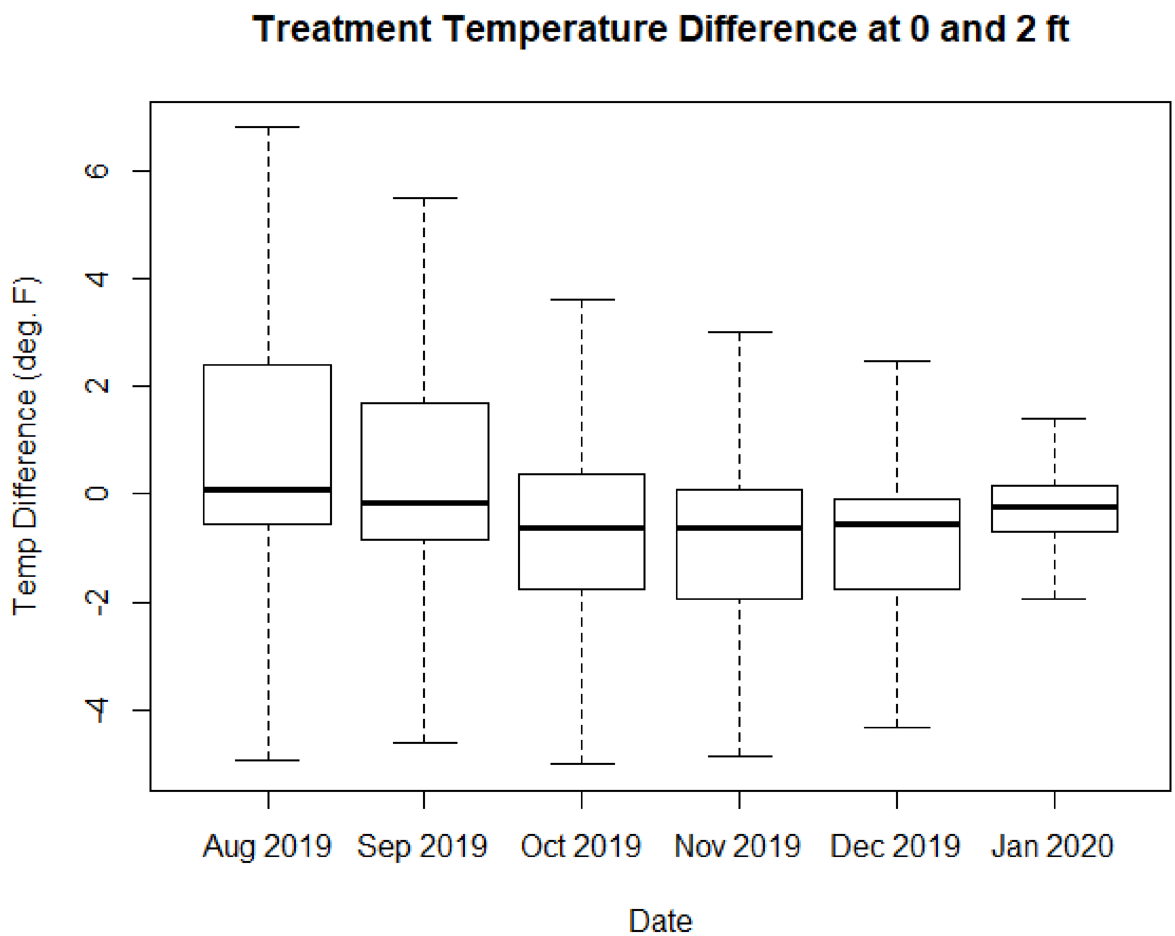


Table 64. Whetstone Treatment Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-5.25	-0.54	0.08	0.99	2.40	8.42
2019 09	-4.86	-0.84	-0.16	0.54	1.70	7.57
2019 10	-8.34	-1.78	-0.62	-0.81	0.38	5.10
2019 11	-6.95	-1.93	-0.61	-0.89	0.07	4.64
2019 12	-8.80	-1.78	-0.54	-1.06	-0.08	3.01
2020 01	-5.33	-0.69	-0.23	-0.32	0.16	3.24

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



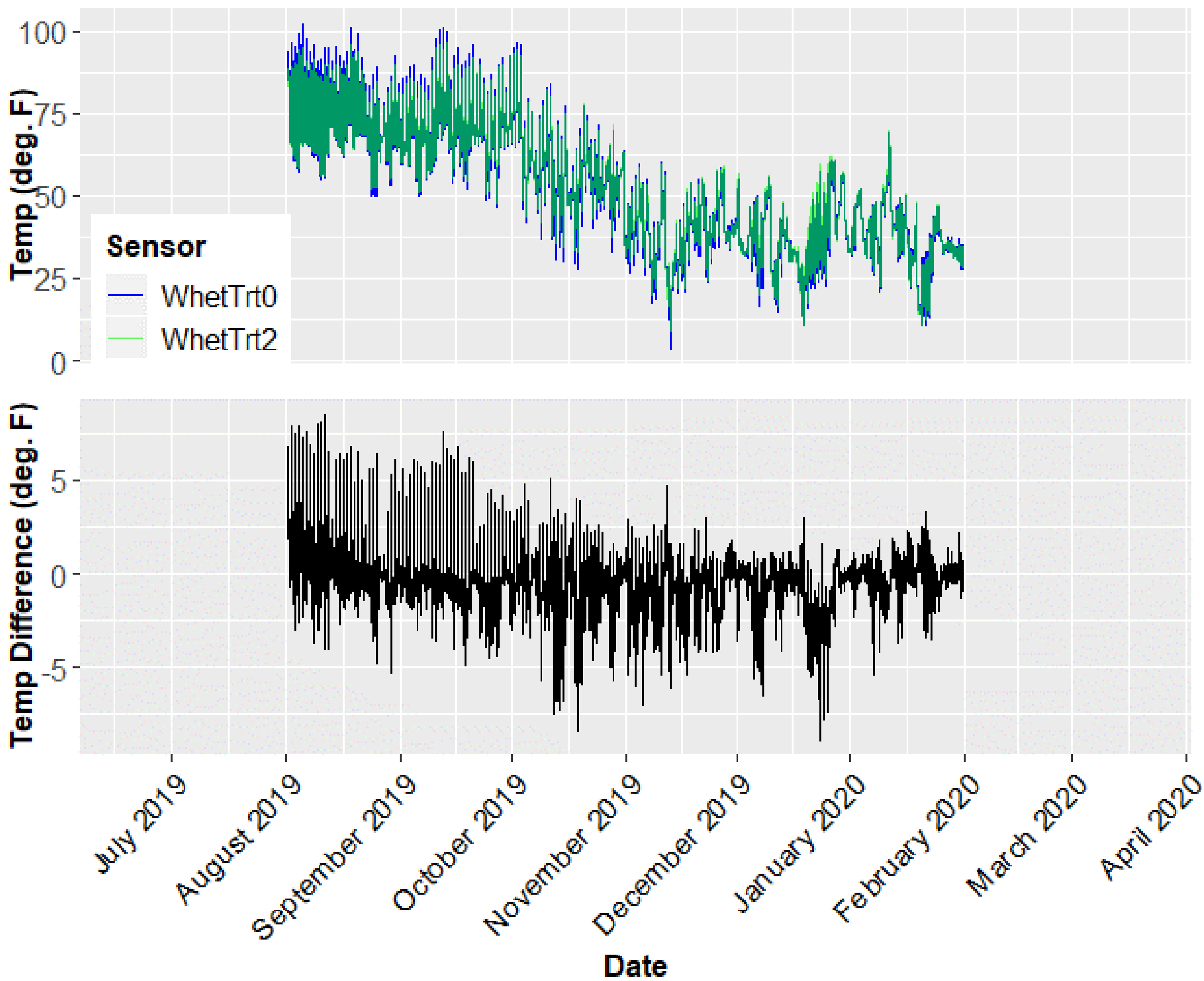
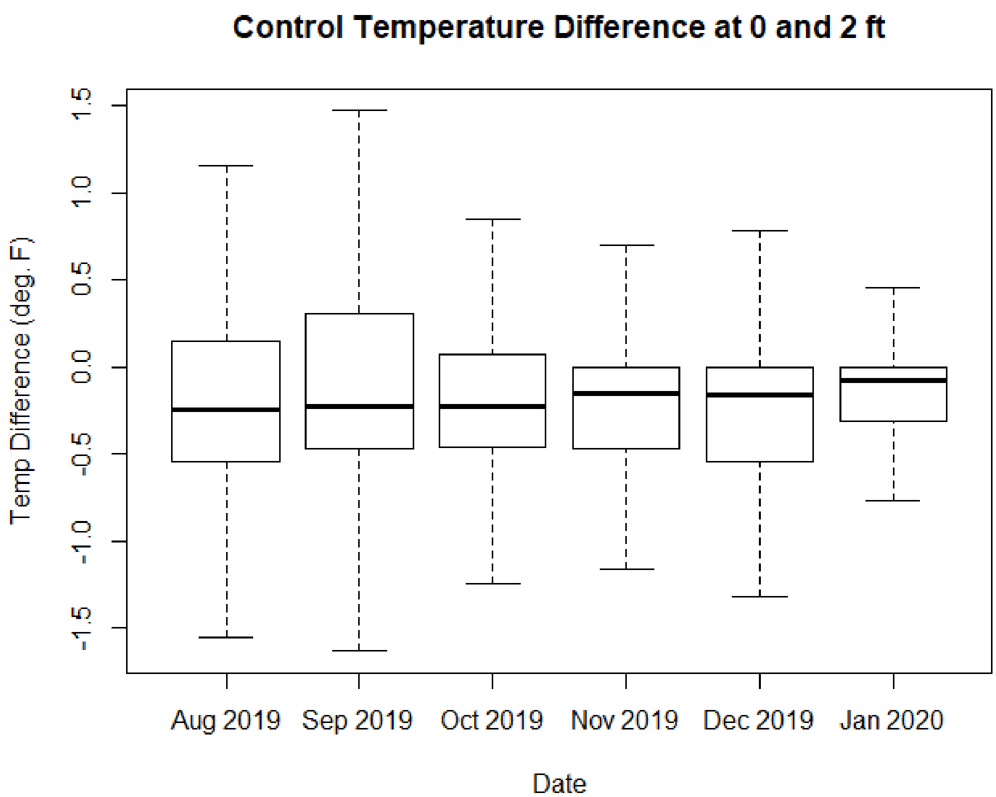


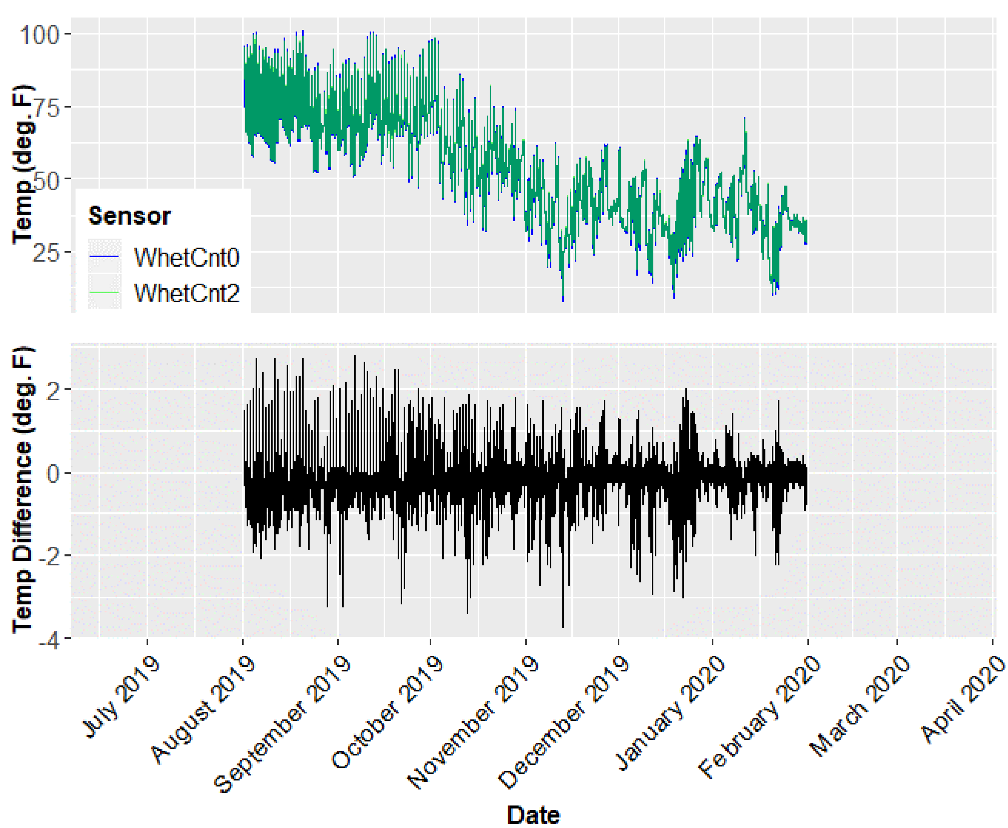
Table 65. Whetstone Control Sensors 0 vs 60 cm

Date	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
2019 08	-3.24	-0.54	-0.24	-0.10	0.15	2.70
2019 09	-3.25	-0.47	-0.23	-0.07	0.31	2.78
2019 10	-3.40	-0.46	-0.23	-0.17	0.07	1.85
2019 11	-3.71	-0.47	-0.15	-0.22	0.00	1.70
2019 12	-3.02	-0.54	-0.16	-0.28	0.00	2.01
2020 01	-2.24	-0.31	-0.08	-0.18	0.00	1.70

Note: Positive values indicate the 0 cm height temperature measured was greater than the 60 cm height. Please refer to Appendix C for the exact dates and times temperature data was recorded for each sensor. The following figures represent the above data.



Control Temperature Difference at 0 and 2 ft
Temp Difference (deg. F)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Aug 2019
Sep 2019
Oct 2019
Nov 2019
Dec 2019
Jan 2020
Date



Temp (deg. F)
100
75
50
25
Sensor
WhetCnt0
WhetCnt2
Temp Difference (deg. F)
2
0
-2
-4
July 2019
August 2019
September 2019
October 2019
November 2019
December 2019
January 2020
February 2020
March 2020
April 2020
Date

Appendix C. Dates of Data Collection for Each Sensor

Type	Site	Height (cm)	Start Date	End Date	Start Date	End Date
Treatment	**Audubon**	**0**	6/27/2019 12:24	8/1/2019 10:24	10/28/2019 10:15	3/17/2020 10:53
Treatment	**Audubon**	**60**	6/27/2019 12:25	3/17/2020 10:54		
Control	**Audubon**	**0**	6/27/2019 12:22	3/17/2020 10:54		
Control	**Audubon**	**60**	6/27/2019 12:22	3/17/2020 10:55		
Treatment	**Blenheim**	**0**	11/6/2019 12:23	3/6/2020 11:44		
Treatment	**Blenheim**	**60**	11/6/2019 12:29	3/6/2020 11:45		
Control	**Blenheim**	**0**	7/24/2019 12:00	3/3/2020 8:19		
Control	**Blenheim**	**60**	7/24/2019 12:00	12/16/2019 14:34	1/15/2020 13:32	3/6/2020 11:50
Treatment	**Canyon**	**0**	7/31/2019 14:32	3/6/2020 12:34		
Treatment	**Canyon**	**60**	7/31/2019 14:34	3/6/2020 12:33		
Control	**Canyon**	**0**	7/24/2019 12:00	3/6/2020 12:30		
Control	**Canyon**	**60**	7/24/2019 12:00	3/6/2020 12:29		
Treatment	**Front**	**0**	8/12/2019 13:02	3/17/2020 10:12		
Treatment	**Front**	**60**	8/12/2019 13:02	3/17/2020 10:13		
Control	**Front**	**0**	8/12/2019 12:00	3/17/2020 10:15		
Control	**Front**	**60**	8/12/2019 12:00	3/17/2020 10:15		
Treatment	**Glenmont**	**0**	7/31/2019 14:38	3/6/2020 12:40		
Treatment	**Glenmont**	**60**	7/31/2019 14:38	3/6/2020 12:38		
Control	**Glenmont**	**0**	8/6/2019 10:58	12/16/2019 14:08	1/15/2020 14:26	3/6/2020 12:56
Control	**Glenmont**	**60**	8/6/2019 10:57	12/16/2019 14:09	1/15/2020 14:27	3/6/2020 12:57
Treatment	**Howlett**	**0**	7/8/2019 13:46	9/6/2019 11:26	12/17/2019 12:54	2/28/2020 9:56
Treatment	**Howlett**	**60**	7/8/2019 13:46	9/6/2019 11:24	12/17/2019 12:48	2/28/2020 9:57
Control	**Howlett**	**0**	7/18/2019 12:35	9/6/2019 11:20		
Control	**Howlett**	**60**	7/18/2019 12:35	9/6/2019 11:17		
Treatment	**Knowlton**	**0**	7/8/2019 13:30	9/4/2019 16:06	1/27/2020 13:34	3/2/2020 10:48
Treatment	**Knowlton**	**60**	6/20/2019 13:00	9/4/2019 16:05	1/27/2020 13:37	3/2/2020 10:47
Control	**Knowlton**	**0**	7/9/2019 8:27	9/4/2019 17:08	1/27/2020 13:28	3/2/2020 10:52
Control	**Knowlton**	**60**	7/9/2019 8:28	9/4/2019 17:09	1/27/2020 13:25	3/2/2020 10:52
Treatment	**Lazarus**	**0**	6/27/2019 15:00	3/17/2020 10:29		
Treatment	**Lazarus**	**60**	6/27/2019 11:11	3/17/2020 10:28		
Control	**Lazarus**	**0**	6/27/2019 11:20	10/16/2019 15:35	12/18/2019 10:31	3/17/2020 10:25
Control	**Lazarus**	**60**	6/27/2019 11:15	3/17/2020 10:25		
Treatment	**Library**	**0**	7/11/2019 14:00	10/17/2019 15:26	1/15/2020 12:38	3/6/2020 10:19
Treatment	**Library**	**60**	7/11/2019 14:00	10/17/2019 15:25	1/15/2020 12:29	3/6/2020 10:18
Control	**Library**	**0**	7/11/2019 13:53	8/9/2019 13:14	1/14/2020 10:49	3/6/2020 10:15
Control	**Library**	**60**	7/11/2019 15:00	8/9/2019 13:14	1/15/2020 12:46	3/6/2020 10:13
Treatment	**Main**	**0**	8/12/2019 12:51	3/17/2020 10:40		
Treatment	**Main**	**60**	8/12/2019 12:51	3/17/2020 10:42		
Control	**Main**	**0**	8/12/2019 12:59	3/17/2020 10:36		
Control	**Main**	**60**	8/12/2019 12:58	3/17/2020 10:37		

Treatment	**Star**	**0**	6/25/2019 14:49	10/17/2019 15:13	1/15/2020 12:11	3/6/2020 10:35
Treatment	**Star**	**60**	6/25/2019 14:49	10/17/2019 15:10	1/15/2020 12:14	3/6/2020 10:33
Control	**Star**	**0**	6/25/2019 14:00	10/17/2019 15:09	1/15/2020 12:04	3/6/2020 10:33
Control	**Star**	**60**	6/25/2019 14:00	10/17/2019 15:09	1/15/2020 12:00	3/6/2020 10:31
Treatment	**Whetstone**	**0**	8/1/2019 11:00	1/31/2020 10:18		
Treatment	**Whetstone**	**60**	8/1/2019 11:00	1/31/2020 10:17		
Control	**Whetstone**	**0**	8/1/2019 10:42	1/31/2020 10:22		
Control	**Whetstone**	**60**	8/1/2019 12:00	1/31/2020 10:23		

References

Ackley, J. W., Angilletta, M. J., DeNardo, D., Sullivan, B., & Wu, J. (2015). Urban heat island mitigation strategies and lizard thermal ecology: landscaping can quadruple potential activity time in an arid city. *Urban Ecosystems*, 18(4), 1447-1459.

Alves Beloqui, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, *239*.

Bouchard, N. R., Osmond, D. L., Winston, R. J., & Hunt, W. F. (2013). The capacity of roadside vegetated filter strips and swales to sequester carbon. *Ecological engineering*, 54, 227-232.

Center for Disease Control. (2017). *Heat-related illness* [Fact Sheet]. Retrieved from https://www.cdc.gov/disasters/extremeheat/pdf/Heat_Related_Illness.pdf

Endreny, T. (2008). Naturalizing urban watershed hydrology to mitigate urban heat-island effects. *Hydrological Processes*, 22(3), 461-463.

Fassman-Beck, E., Hunt, W., Berghage, R., Carpenter, D., Kurtz, T., Stovin, V., & Wadzuk, B. (2016). Curve number and runoff coefficients for extensive living roofs. *Journal of Hydrologic Engineering*, 21(3), 04015073.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., ... & Mikkelsen, P. S. (2015). SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525-542.

Ichinose, T., Matsumoto, F., & Kataoka, K. (2008). Chapter 15 – Counteracting urban heat islands in Japan. *Urban Energy Transition from Fossil Fuels to Renewable Power*. 365-380.

Imhoff, M. L., Zhang, P., Wolfe, R. E., & Bounoua, L. (2010). Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment*, *114*(3), 504-513.

Jartun, M., Ottesen, R., Steinnes, E., & Volden, T. (2008). Runoff of particle bound pollutants from urban impervious surfaces studied by analysis of sediments from stormwater traps. *The Science of the Total Environment*, *396*(2-3), 147-63. doi:10.1016/j.scitotenv.2008.02.002

Kaiser, A., Merckx, T., & Van Dyck, H. (2016). "The Urban Heat Island and its spatial scale dependent impact on survival and development in butterflies of different thermal sensitivity." *Ecology and Evolution*, 6(12), 4129-4140.

Kazemi, F., Beecham, S., & Gibbs, J. (2009). Streetscale bioretention basins in Melbourne and their effect on local biodiversity. *Ecological Engineering*, 35(10), 1454-1465.

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, *197*, 522-538.

Moore, T. L., & Hunt, W. F. (2012). Ecosystem service provision by stormwater wetlands and ponds–a means for evaluation?. *Water Research*, 46(20), 6811-6823.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108,* 455, 1-24.

Razzaghmanesh, M., Beecham, S., & Salemi, T. (2016). The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening, 15,* 89-102.

Ruddell D., Hoffman D., Ahmad O., and Brazel A. (2013) Historical threshold temperatures for Phoenix (urban) and Gila Bend (desert), central Arizona, USA. *Climate Research*. 55:201–215. doi:10.3354/cr01130

Sexton, J. P., P. J. McIntyre, A. L. Angert, and K. J. Rice. (2009). Evolution and ecology of species range limits. *Annual Review of Ecology, Evolution, and Systematics*. 40: 415– 436.

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban Form and Extreme Heat Events: Are Sprawling Cities More Vulnerable to Climate Change Than Compact Cities?. *Environmental Health Perspectives, 118,* 10, 1425-1428.

Susca, T., Gaffin, S., & Dell'Osso, G. (2011). Positive effects of vegetation: Urban heat island and green roofs. *Environmental Pollution, 159*(8-9), 2119-2126. doi:10.1016/j.envpol.2011.03.007

Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D. N., & Papakatsikas, C. (2011). Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. *Building and Environment, 46,* 1, 38-44.

Voyde, E., Fassman, E., Simcock, R., & Wells, J. (2010). Quantifying evapotranspiration rates for New Zealand green roofs. *Journal of Hydrologic Engineering*, 15(6), 395-403.

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Science of the Total Environment*, 553, 83-95.

Xiao, Y., Zhang, T., Liang, D., & Chen, J. (2016). Experimental study of water and dissolved pollutant runoffs on impervious surfaces. *Journal of Hydrodynamics, 28*(1), 162-165. doi:10.1016/S1001-6058(16)60617-0

Yang, L., Qian, F., Song, D.-X., & Zheng, K.-J. (2016). Research on Urban Heat-Island Effect. *Procedia Engineering, 169,* 11-18.

Yang, W., & Omaye, S. T. (2009). Air pollutants, oxidative stress and human health. *Mutation Research - Genetic Toxicology and Environmental Mutagenesis, 674,* 45-54.